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Modeling of Energy Storage Systems for Building Intergation

Azadeh Mazaheri

University of Wisconsin-Milwaukee

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MODELING OF ENERGY STORAGE SYSTEMS FOR BUILDING INTERGATION

by

Azadeh Mazaheri

A Thesis Submitted in

Partial Fulfillment of the

Requirements for the Degree of

Master of Science

in Engineering

at

The University of Wisconsin- Milwaukee

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ABSTRACT

MODELING OF ENERGY STORAGE SYSTEMS FOR BUILDING INTERGATION

by

Azadeh Mazaheri

The University of Wisconsin-Milwaukee, 2015

Under the Supervision of Dr. Adel Nasiri & Dr. Dan M. Ionel

An advanced Energy Storage device modeling, namely, Zinc Bromide, is proposed to integrate a new software Smartbuilds, developed by Marquette University, based on an integrated building. Smartbuilds will provide the platform to integrate all the components of the proposed Building, which incorporate with renewable energy and energy storage system. The zinc bromide modeling results show that the battery's open-circuit voltage is a direct function of the state of charge (SOC) of the battery. Furthermore, resistance is also a function of the state of charge at constant temperature. A Coulomb Counting technique is used to adjust the estimated SOC according to battery current. Simulation studies are made with Matlab/Simulink. Proposed Zinc bromide battery model has been compared with Energyplus, building energy simulation program, battery model and it has been translated into an Energyplus' battery model to integrate in Energyplus. Example case studies are provided to show the results. . . .

*Dedicated to my husband for his infinite love, support, and
encouragement*

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...

“Thanks to my solid academic training, today I can write hundreds of words on virtually any topic without possessing a shred of information, which is how I got a good job in journalism.”

Dave Barry

Chapter 1

Introduction

1.1 Research Background

Buildings account for about one-third of the energy consumed in the United States. Heating and cooling systems use 60 percent of this energy, while lights and appliances use another 40 percent in which 18 percent for commercial and 22 percent for residential buildings [1]. As shown in figure 1.1, the building sector bears the largest energy usage compared to the transportation sector (29 percent) and the industrial sector (30 percent), and accounts for about 2/3 of the U.S [2]. Electricity consumption in 2010 figure 1.1. As a consequence, the CO₂ emission from the buildings is also significant. About 39 percent of the U.S. total carbon emissions are coming from the building sector with 18 percent from the commercial buildings and 21 percent from the residential buildings [3].

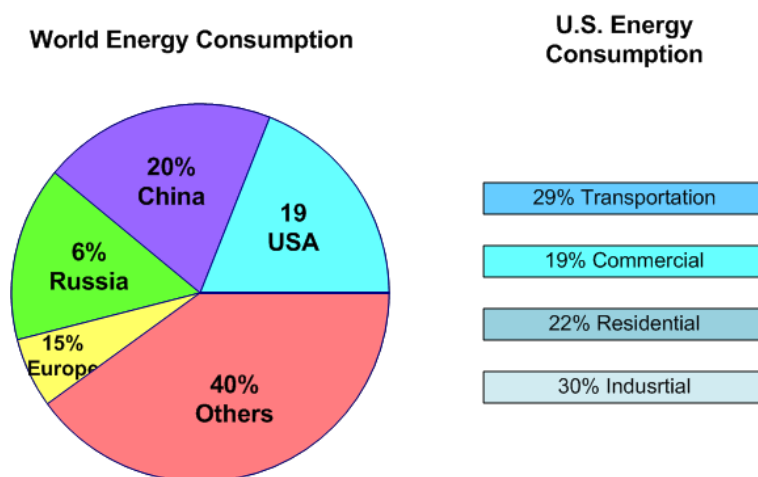


FIGURE 1.1: Energy consumption in 2012. Source: U.S. energy information administration.

Integration buildings with renewable energy sources is a good solution to reduce energy dependency and greenhouse gas emissions. So distributed on-site power generation in buildings is one potential technological solution to achieve the net-zero energy building design goal and reduced energy consumption in buildings dramatically. Representative technologies include micro-Co generation and building-integrated PVs and wind turbines [4]. Renewable energy solutions are designed to increase energy security and independence, while reducing your long-term energy costs and environmental footprint [2]. So buildings integrated renewable energy sources such as wind or solar have two advantages: decreasing the energy consumption and increasing the local energy generation.

As it mentions above the heating, ventilation and air conditioning (HVAC) system use a large portion of energy in buildings, while buildings integrated renewable energy sources are good for local generation of clean power. Decreasing energy consumption causes electricity saving in buildings which will have momentous advantages for the power sector, permitting to reduce the investment in generation and distribution assets and also allowing electrical companies to augment their clients without significant network expansion or high investments in new power plants. As a result, the idea of use of energy from renewable sources in the buildings sector is highly recommended currently.

Wind and PV are typical renewable energy sources which can integrate to the buildings. The problem with integrated building with wind or PV is that renewable energy sources are variable and intermittent so we can't be scheduled and dispatched wind or PV energy sources like conventional sources. It means we can't rely on them 100%. Also the inherent temporal mismatch between the availability of intermittent wind or sunshine and the variability of demand is the another obstacle to getting a large fraction of our electricity from renewable sources. A cost-effective means of storing large amounts of electrical energy could solve this problem. So electrical storage is an important component in distributed power systems these days. In addition, with the increasing attention to electricity grid and building interactions, such as demand response technology, electrical storage modeling is expected to be used more often [4].

In conclusion, to integrated renewable energy sources in buildings and to have a reliable energy source, storage devices like battery, water tank, and ice/heat storage unit play an important role because they can manage using renewable energy sufficiently. An energy storage device can provide shifting energy from light demand hours in the early mornings to heavy demand in the late afternoon and early evening. Energy storage devices support renewable energy sources. So supporting renewable energy sources with energy storage technologies make our environment benefits from reducing CO2 emissions.

As a consequence, its necessary to consider an appropriate battery for buildings with renewable energy sources to cope with fluctuations in demand. It means battery is

needed in these type of buildings to export electricity to the battery when there is a surplus production, and drawing electricity when need it. In addition Storage devices play a very important role in reducing energy consumption and cost in building energy systems since they can improve the efficiency of renewable energy resource utilities and the flexibility of time-of-use (TOU) electricity prices [5]. Chapter four of this thesis is devoted to such topics.

Furthermore, its crucial to develop a software to model energy use in buildings and calculate energy consumption and production in buildings. Energyplus is used for this mentioned objective. EnergyPlus is a building energy simulation program that helps us to model the usage of energy and water in buildings. Also, it models, lighting, heating, cooling, ventilation, water usage, and other energy flows. So it provides a way to optimize the building design to reduce usage of energy and water. EnergyPlus models heating, cooling, lighting, ventilation, other energy flows, and water use. EnergyPlus has many incredible simulation capabilities: time-steps less than an hour, modular systems and plant integrated with heat balance-based zone simulation, multi zone air flow, thermal comfort, water use, natural ventilation, and photo voltaic systems. Various building energy simulation programs developed around the World. EnergyPlus can install on the Windows, Macintosh, and Linux platforms. The U.S. Department of Energy (DOE) began planning for a new generation of simulation tools in 1995. They collaborated with two development teams to come up with Energyplus. EnergyPlus compress completely new code written in Fortran 90.

The major goal of this master thesis first introduces and modeling Zinc Bromide battery. Then comparing this battery with Energyplus kinetic battery model. Then translating and integrating Zinc Bromide battery to Energyplus battery model. Also purchased energy will be analyzed to show the effect of battery. Chapter five of this thesis is devoted to such topics.

1.2 Objective

The main objective of this master thesis is to develop an appropriate battery model, for the building sector and integrate the model in an energy analysis program, Energyplus.

To fulfill the mention goal, the following activities must be done:

- Analyze criteria and concept regarding to energy storage systems.
- Development of a battery model suitable to be used for building sector.

- Analyze criteria and concept regarding to building energy simulation, Energyplus.
- Discussion and implementation of Energyplus battery models and compare with the selected battery model.
- Translate the proposed battery model in an Energyplus acceptable format to integrate the model in Energyplus.
- Evaluate and validate the proposed battery model with running different examples in Energyplus.

1.3 Master Thesis Layout

This master thesis is divided into six chapters with the following structure: In chapter 1, an introduction concerning the main objectives of the thesis is presented.

Chapter 2, presents the state of the art regarding the assessment in the selection of energy storage systems for the building sector. Firstly, various types of renewable energy concept is introduced. Then, renewable energies suitable to be used for building sector are explained. Next, different type of energy storage systems is discussed. Finally, application of energy storage in buildings is implemented.

Chapter 3, focuses on Energyplus software and an example of building modeling in Energyplus is reviewed.

In chapter 4, a battery model is developed by using Matlab Simulink. Then Energyplus battery model is discussed and finally Energyplus battery model is compared to the proposed battery model.

In chapter 5, SmartBuilds software, which is developed by Marquette University, is discussed. Then, the original contribution of this thesis, integration of the battery model, is presented. Finally, study cases are carried out under different scenarios.

Chapter 6, presents conclusion with a summary of work and original contribution.

Chapter 2

Review of State of the Art

2.1 Types of Renewable Energies

First, we should know what are renewable energy sources. Renewable energies exists in the nature freely. Some of them are infinite while some of them have a finite amount in the nature. Also, some of them like wind or sun are available naturally to use, but some of them like coal should be formed. Renewable energy sources are carbon neutral. It means they dont create carbon components like CO₂ which causes air pollution. Renewable energy sources are constantly and sustainable replenished. It means they will not run out and this is the reason that they're called green energy. Renewable energy sources can be converted to electricity, then stored or transported to our homes. Figure 2.1 shows different type of renewable energy sources..

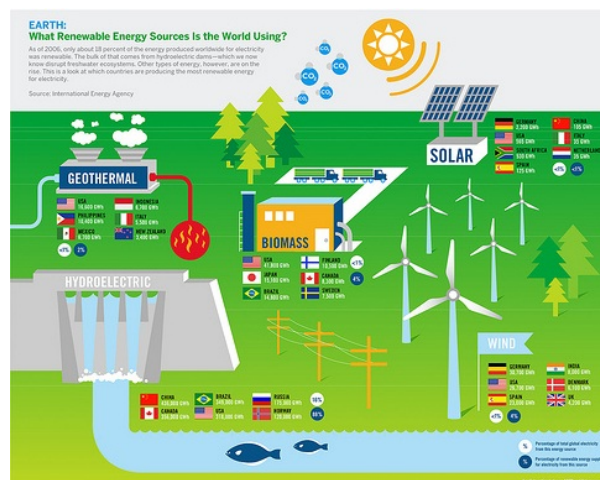


FIGURE 2.1: Different types of renewable energy sources. Source: www.eschooltoday.com/energy/renewable-energy/

The different types of renewable energies will be clarified in this section. There are various types of renewable energies like wind, solar, biomass, hydro and geothermal which come from natural infinite sources. Most of them depend on sunlight directly or indirectly. They replenish themselves quickly and constantly as part of the normal life cycle. They will never run out since they are not depleting any resource to create the energy. Also, they are cleaner sources of energies in the world.

In the United States fossil fuels, which draw on finite resources, such as coal, oil, and natural gas are used heavily to produce energy. These types of energy sources are too expensive and also damage our environment. In contrast using renewable energy sources benefit us in many aspects such as reducing pollution, reducing reliance on fossil fuels, repressing global warming, creating new jobs and new sources of income, and protecting environmental values such as habitat and water quality.

2.1.1 Solar Power

Solar energy is power from the sun. Sun is the base for all types of energy that we use. The sun causes plants to grow and it releases when a biomass fuel burns. It can be stored in swamps and compressed underground for a long time in the form oil and coal. Sun energy makes temperature differences and it ends up to produce wind that can rotate wind turbine. Sun energy causes the water evaporating which falls on high elevations and rushes down to the sea. So it causes to spin hydroelectric turbines by passing through. But solar energy refers to the ways which suns energy can produce heat, lighting, and electricity directly.

With two different technologies, solar collectors and photo voltaic panels, we can convert suns energy into electricity. Photo voltaic (PV) Solar cells are one of the fastest growing energy sources. They made from silicon to absorb sun energy to produce electricity. The photo voltaic system involves the movement and displacement of electrons to convert light into electrical direct current (DC). Solar cells are becoming more efficient, transportable and even flexible, allowing for easy installation [6].

A PV cell contains a semiconductor p-n junction which converts lights electromagnetic radiation into the electricity. When the PV cell is exposed to light, absorbed photons create hole-electron pairs near the p-n junction. Under the influence of the internal electric fields in the depletion region, the holes will be moved into the p-side and the electrons will be pushed into the n-side [7]. In the two sides, there is a difference which causes producing a voltage. Current can be driven to a connected load by the produced voltage. PV output energy is proportional with the solar insulation and temperature.

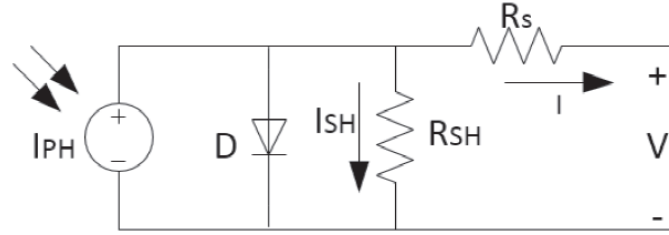


FIGURE 2.2: PV cell simple equivalent model. Source: Gilbert M. Masters, Renewable and efficient electric power systems, 2004.

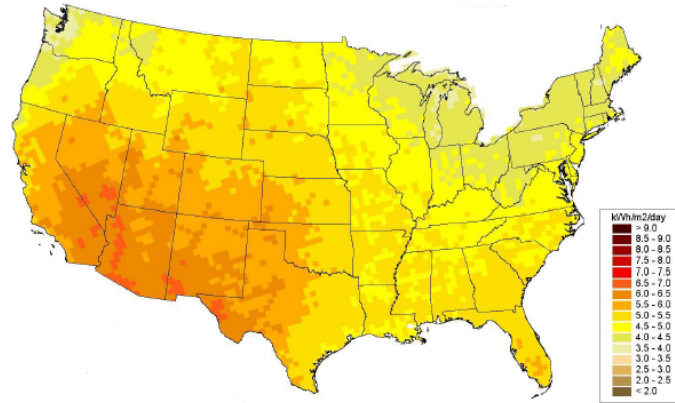


FIGURE 2.3: U.S. annual solar insolation. Source: Union of Concerned Scientists.

Figure 2.2 shows photo voltaic's simple equivalent model which consists of an ideal current source and a real diode which is in parallel with the current source.

Clean solar energy technologies in recent years have largely begun to expand into residential areas since sun energy provides light and heat to our buildings if buildings are designed properly to capture the sun's heat in the winter and minimize it in the summer. Solar energy technologies are considered to grow significantly in the 21st century. Figure 2.3 shows US annual isolation.

2.1.2 Wind Power

Air current is captured by wind turbine and convert into usable energy. The wind turbine is one of the most popular renewable technologies to integrate to the buildings. It provides a significant amount of needed electricity around the world. Wind power generates clean, sustainable electricity for us from wind power doesn't contribute to produce any kind of global warming emissions.

Wind power is the conversion of kinetic energy, which come from the movement of the air with various temperature and pressure at the Earth's surface into a useful form of energy like electricity while it doesn't produce any type of pollution. The power available from

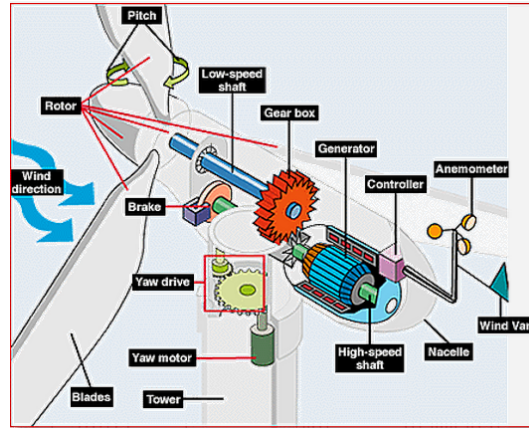


FIGURE 2.4: Wind turbine components. Source: Union of Concerned Scientists.

the wind is proportional with cube of the wind speed, so as wind speed increases, more energy is produced. Wind energy production is growing rapidly these days. Now 1.5 percent of electricity use in the world come from wind turbine which extract electricity from the breeze.

There are a few different types of wind turbines that are selected according to our use. The typical type is the horizontal axis design. In this design, two or three blades rotate upwind of the tower. To provide power off the grid, small wind turbine is used. The range of producing power in small wind turbine is between 250-watt to 50-kilowatt. To provide power to a grid, large wind turbines are used by utilities. The range is between 250-kilowatts up to 3.5 to 5 MW. Utility-scale turbines are place in wind farm to provide enough power for thousands of homes.

Wind turbine includes three big parts: the tower, nacelle, its a box behind the blades, and the blades. The nacelle is a box where motion is converted into electricity. Figure ?? shows different parts of a wind turbine. In common design, the blades are connected to an axle, which runs into a gearbox. The speed of the rotation is stepped up by the gearbox. The speed of the generator varies since the wind speed varies. So it ceases to produce fluctuation in the electricity and its a big problem for utilities need constant voltage. To make speed turbines constant, wind speed should be slow down when wind speed gust. Also power controls can be applied to fix this problem if variable speed turbines are used. In addition, a low speed generator can be used to overcome this problem. There are upper and lower wind speed limits, cut in and cut out, that wind turbines can work in that limit. If the wind is too slow, blades cant rotate and there is no power. Too fast wind can be damaged the equipment.

In 2012, 13,351 MW of wind power installed in the united states, which provide electricity for under four percent of U.S. electricity generation. Wind power plays an important role

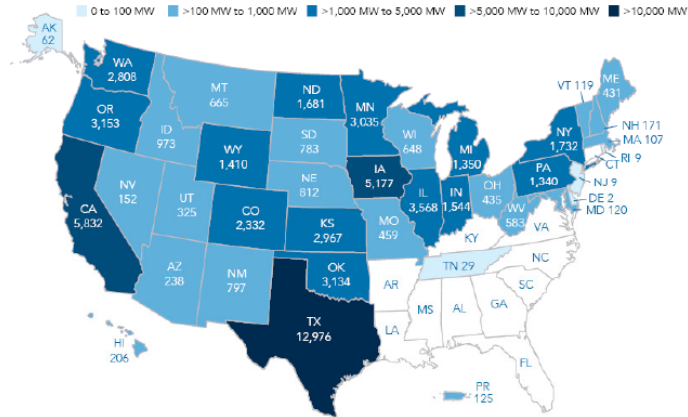


FIGURE 2.5: Wind installations in US States. Source: Energy Information Administration (EIA), 2010.

to move toward a sustainable energy in the future. Figure 2.5 shows wind installations in U.S. states.

2.1.3 Biomass

Biomass, is one of the sources of renewable energy in the world, which comes from plant, crop, animal waste, and forest. It's one of the oldest type of renewable energy since our ancestors learned to make fire. It refers to chemical material that can be stored and then produce energy. Biomass can re-generate over a short period of time. Biomass is a natural battery which stores solar energy for plants capture the sun's energy. The captured energy from the sun will be released when burning wood. Biomass can be used in ways which increase global warming pollution like using Wood from trees to produce energy for heating and cooking or ways that can help clean up our environment. Biomass could include biodegradable wastes which can use as fuel. To replace biomass with fossil fuels, we should be ensuring that biomass produce energy in ways that protect the environment like protecting soil quality, avoiding erosion, and maintaining wildlife habitat. Now biomass can convert efficiently to electricity. Burning biomass sources to produce heat is the typical way to capture the energy from biomass. Biomass fired steam power is used to produce electricity. In the United States, we already get over 50 billion kilowatt-hours of electricity from biomass, providing nearly 1.5 percent of our nation's total electric sales. Biomass was the largest source of renewable electricity in the U.S. until 2009, when it was overtaken by wind energy. Biopower accounted for more than 35 percent of total net renewable generation in 2009, excluding conventional hydroelectric generation [8].

2.1.4 Hydroelectric

On the Earth, water is moved constantly which is called hydro logic cycle process. Clouds are formed by Evaporated water from the oceans, then evaporated water falls down as rain and snow into streams and rivers, and come back to the sea. All this movement helps us to capture useful energy.

Hydroelectric energy relies on water. Hydroelectric power comes from capturing the energy of moving water by using dams. To capture the kinetic energy in moving water, water should move with an appropriate speed and volume. So it can rotate a turbine which creates magnets inside a generator to rotate and generate electricity. Dams are used to provide enough volume of moving water.

Hydroelectric power is the largest source of emission free renewable power in the world and U.S. Its produced by using the gravitational force of falling or flowing water. Falling or flowing water must be controlled to get energy from it. Engineers usually create reservoir or dam rivers to channel water so it will be easy to control the amount of water and consequently the amount of produced energy. This extracted energy turn turbines and turbines make generators move to produce electricity. Producing the power of water is a safe environmental choice but it has some environmental concerns like blocking the migration of fish.

In the United States, 78 GW electricity was produced by hydroelectric power in 2011 but with growing other renewable energy technologies such as wind and solar, it drops significantly in 2012.

2.1.5 Geothermal

Another source of energy is storing heat in the earth which can utilize in many ways. This heat energy, known as geothermal energy. A layer of molten and hot rock exists under the earths crust which is called magma. Heat always is in this layer. Existing heat in 10,000 meters of earths surface holds 50,000 times more energy than natural gas and oil resources.

Geothermal energy is the earths internal heat that can be extracted through natural processes. It usually finds in the rock and fluids beneath the earths crust. It can be used in many ways like cooking and heating. Also in large scale it can be used to produce electricity.

To capture the energy from geothermal sources, hydrothermal convection systems are used. Cooler water heats up when it seeps into the earths crust and then it wants to

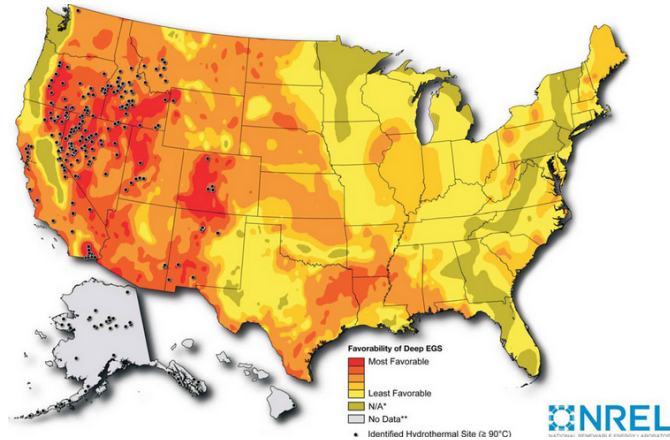


FIGURE 2.6: U.S. geothermal resources. Source: National renewable Energy Lab.

rise to the surface. Its formed in steam if its forced to rise to the surface. The produced steam is used to drive electric generators and produce electricity.

In the United States, 68 billion kilowatt-hours of electricity are produced by geothermal, which is enough for more than 6 million typical U.S. households. Figure 2.6 shows U.S. geothermal resources.

2.2 Renewable Energies in Buildings

Buildings account for about one-third of the energy consumed in the United States [9]. HVAC (heating, ventilation and air conditioning) system uses 60 percent of this energy which is a large portion of building energy consumption, while lights and appliances use another 40 percent. Manufacturing and transporting building materials require additional energy [9]. By capturing the natural wind, the sun's light and its isolation energy, and also by using other renewable energy sources like solar water heating systems, buildings energy consumption will be reduced significantly. Figures 2.7 and 2.8 shows examples of integrated home with renewable energy sources. Integrating renewable energy sources in the buildings has result in economy by saving money and reducing the need for fossil fuels, increasing energy security and independence and also improving the environment.

To make buildings should be safe, comfortable, functional, and environmentally friendly with high energy efficiency, renewable energy sources should be integrated into the buildings. So energy dependency and greenhouse gas emission will significantly reduce in this type of buildings which is called green buildings.

Green buildings are sustainable buildings designed to be environmentally responsible and resource efficient [10]. Energy consumption is reduced and local energy generation



FIGURE 2.7: Building integrated with PV. Source: U. S. Department of Energy, Building Technologies Program, 2011.



FIGURE 2.8: Building integrated with wind and PV. Source: U. S. Department of Energy, Building Technologies Program, 2011.

increases in green buildings. In other words, buildings integrated with renewable energy sources benefit us from efficient power generation and efficient operation of the existing building equipment.

Energy efficiency and use of renewable/clean energy have become key factors for contemporary building development [10]. Recently, the Green Building concept has drawn contemporary building development and it has drawn much attention worldwide, which aims to achieve sustainable, environmentally responsible and resource efficient buildings [11]. The so-called Net-Zero Energy Building (NZEB) has been well received as the goal to be implemented for the decades to come [11]. Increasing of energy efficiency of the existing buildings with HVAC equipment, and also integrating renewable energy resources like wind and solar into the buildings to generate efficient power are required

to develop NZEB. The Green Building is also referred as Sustainable Building or High Performance Building [12]. The green building design aims to reduce the overall impact from the building construction, equipment operation and maintenance, energy and resource consumption, and pollution of the buildings on both of the indoor and outdoor environments [12]. Recently the idea of sustainable construction and maintenance has become very attractive and popular in the architectural design field and building research area. The NZEB concept reflects the accompanied viewing for energy usage in green buildings [13]. The U.S. DOE and its National Renewable Energy Laboratory (NREL) have defined the NZEB as follows: A net-zero energy building (NZEB) is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies [14]. The U.S. DOE has also established goals for creating the technology and knowledge base for cost effective net-zero energy commercial buildings by 2025 [14]. The energy efficiency and the renewable energy sources are both important factors in NZEB. Developing NZEB requires buildings integrated with Renewable power sources, like wind and solar. Solar energy is a preferable renewable energy source in buildings, since its zero-emission nature and plentiful availability, misplacing the daytime demand for the electric power from fossil fuels, and low operation and maintenance cost.

2.3 Energy Storage Systems

Renewable energy sources will be part of the energy mix for a sustainable future, but issues of load peak-valley difference, security and stability of power system, as well as large-scale development and utilization of intermittent renewable energy represented by wind and solar, promote the application process of electric energy storage technologies in power system [15]. Energy storage technology, which can isolate the production and use of electrical energy, plays important roles in restraining wind power output fluctuations, improving power quality, peak load shifting, frequency regulation of power grid, etc. [15].

The energy storage system can store and discharge energy so they have an important role for integrated buildings with renewable energy systems. Energy storage solution that can be coupled with renewable energy systems improves energy sustainability and dispatch in green houses. Energy storage considerably reduces the intermittent effect of the renewable source and enhances green Power dispatch, resulting in a dramatic increase in the renewable energy value proposition [16].

The energy storage system helps to overcome the challenge that we have with using renewable energy sources. Intermittent, non-scheduling, and randomness of renewable

energy sources causes difficulty in having a safe and stable operation of the power system. Energy storage systems help us to solve this problem.

Electric energy can be stored if it is converted into mechanical energy, chemical energy, electromagnetic energy, or other forms [15]. Energy storage technology can be divided into four major types of mechanical energy storage, electrochemical energy storage, electromagnetic energy storage and the phase change, energy storage, depending on the difference of energy storage technology [15]. Electrochemical energy storage technologies represented of Li-ion batteries, sodium sulfur batteries and vanadium Redox flow battery, meet the power system technologies application requirements and smart grid development trends, for the high power density, siting flexibility and fast response characteristics [15].

For taking renewable energy sources into the buildings, electrical energy storage device is highly required to manage power supply at any time. Also energy storage system can make renewable energy smooth.

There are different approaches to stored energy around the world which can be divided into six main categories:

- Solid state or electrochemical batteries: They include advanced chemistry batteries and capacitors.
- Flow or Redox batteries: In this type, the battery's energy is stored in the electrolyte directly so they have a longer cycle life and quick response times. They also are electrochemical type.
- Flywheels: They are mechanical devices which utilize rotational energy to deliver instantaneous electricity. This type of battery is mechanical type.
- Compressed air energy storage: It harnesses compressed air to produce a potent energy reserve. This type of battery is mechanical type.
- Thermal: It seizes, heat and cold to produce energy on demand.
- Pumped hydro power: It produces large scale stores energy with water. This type of battery is mechanical type.

2.3.1 Electrochemical Batteries

On a basic level, a battery is a device which has one or more electrochemical cells that convert stored chemical energy to electrical energy. Each cell has a positive terminal,

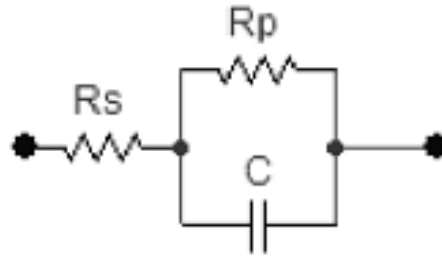


FIGURE 2.9: Electrochemical capacitor energy storage equivalent model, based on the concept proposed John R. Miller and S.M. Butler, ECT Transaction, 2008.

cathode, and a negative terminal, anode. Ions move among terminal and electrodes because of electrolytes. So current flows out of the battery.

Battery systems have been improved with progressing in chemical field. There are four different types of solid state batteries:

Electrochemical Capacitors: They sometimes appear under different names like electric double layer, super-capacitor or ultra-capacitor. In this type of battery electrical charge is stored physically at a surface electrolyte interface of high-surface-area-carbon electrodes so the process is fast and highly reversible; also the discharge- charge cycle can be repeated over and over [17].

Electrochemical capacitor energy storage has three components which are shown in figure 2.9. Energy is lost in charging and discharging period by R_S and self-discharge energy is lost by R_p . In this type of battery, current flows into this battery when two electrodes are connected till the battery charges completely. When voltage is applied, the capacitor comes back to its charge.

Lithium-Ion (LI-ION) batteries: They are one of the most popular type of battery which use in electric vehicles (EVs). Lithium-Ion batteries have different chemistry not only single electrochemical couple. Lithium-Ions transfer between electrodes during the charge and discharge cycles.

The characteristic of this type of battery is high power density, excellent performance, proper energy density, long life cycle, high columbic efficiency, and low self-discharge characteristics. Batterys energy density, life time, voltage characteristics, and safety are extremely affected by the electrode material. Combination of nickel, cobalt aluminum (NCA) nickel, manganese cobalt (NMC), and iron phosphate (LFP) considers as a cathode or positive electrode, while lithium titanate and graphite are considered as an anode or negative electrode. Figure 2.10 shows one time constant equivalent model of Lithium-Ion battery.

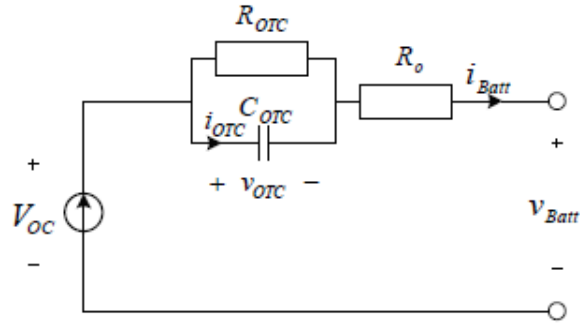


FIGURE 2.10: Lithium-IOn energy storage one time constant equivalent model, based on the concept proposed by Ahmad RAHMOUN, Helmuth BIECHL, University of Applied Sciences Kempten, 2012.

Nickle-Cadmium (NI-CD) batteries: They are a traditional type of battery which provide long life and reliable service; while they dont have a complex management systems. The positive terminal is Nickle and the negative terminal is Cadmium. Till 1980s, NiCd was popular battery choice for emergency medical equipment, two-way radios, professional video cameras, and power tools. In this type of battery, memory effect makes capacity loss if a periodic full discharge cycle wont give. The previous delivered energy is remembered by the battery and it does not want to give more when a routine has been established.

Sodium Sulfur (NAs) batteries: Sodium Sulfur energy storage uses for large scale applications, because they operate at a high operating temperature of 300 C - 350 C. High-temperature thermal control benefits this type of battery to operate in high temperature with no safety problem of specific usage. The characteristics of this type of battery are inexpensive materials and are, high power, high columbic efficiency up to 90%, acceptable thermal behavior, and long life cycle. The primary applications are large scale power and energy support, such as load leveling, renewable energy integration, and UPS systems. In Sodium Sulfur battery, the active materials are melted Sulfur as positive electrode and molten sodium as the negative [17]. Sodium is a dangerous material since it can burn spontaneously in contact with air and moisture, it is also highly corrosive. Solid ceramic/alumina separates the electrodes in Sodium Sulfur batteries. The electrochemical reaction between Sodium and Sulfur causes this battery to work. Figure 2.11 shows tubular sodium-Sulfur battery design. In this design sodium is a central electrode.

2.3.2 Flow or Redox batteries

Flow batteries are a type of rechargeable battery where rechargeability is provided by two chemical components dissolved in the liquid contained within the system and most

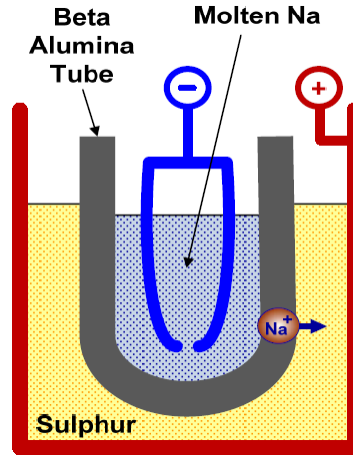


FIGURE 2.11: Sodium-Sulphur energy storage schematic model, based on the concept proposed in HYFUSEN, 2011.

commonly separated by a membrane [17]. Flow batteries are known under Redox name. Redox refers to chemical reduction and oxidation reactions employed in the RFB to store energy in liquid electrolyte solutions which form through a battery of electrochemical cells during charge and discharge [17].

The most important advantage of flow batteries is they can be recharged instantly. Different types of the flow battery are Iron-Chromium (ICB) flow battery, Vanadium Redox (VRB) flow battery, and Zinc Bromine (ZNBR) flow battery.

The difference between flow cell batteries and conventional batteries is that energy is stored as the electrolyte material in flow cells while its stored as the electrode in conventional batteries.

Iron-Chromium (ICB) flow batteries: They are a Redox flow battery (RFB) which energy is stored by employing the $\text{Fe}^{2+} - \text{Fe}^{3+}$ and $\text{Cr}^{2+} - \text{Cr}^{3+}$ Redox couples [17]. The active chemical species are fully dissolved in the aqueous electrolyte [17]. This battery has an efficiency between 70 to 80 %. Iron-Chromium (ICB) flow battery can operate well at high temperature so its suitable for warm climates.

energy by employing Vanadium Redox couples [17]. These active chemical species are fully dissolved at all times in Sulfuric acid electrolyte solutions [17]. Vanadium redox flow batteries (VRBs) can overcome cross contamination, degradation of Redox flow battery since it uses only one element (vanadium) while Redox flow battery uses more than one element. Concentration of vanadium in this type of battery defines the energy density. Vanadium redox flow battery operates in a small range of temperature since the number of vanadium ions is limited. This limitation causes low energy density of this type of battery. Also expensive polymer membranes are required because of the highly acidic and oxidative environment which increase the capital cost. This battery

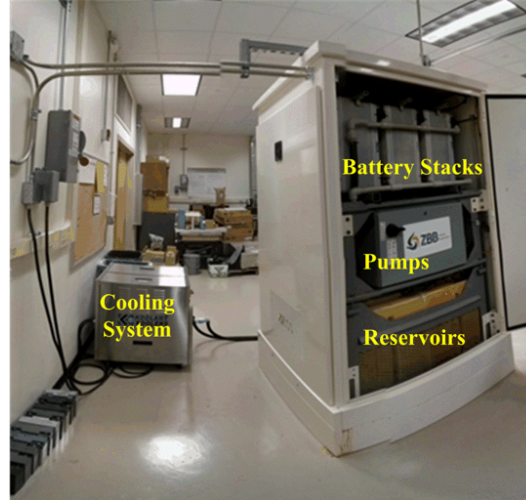


FIGURE 2.12: Zinc-Bromide (ZnBr) flow battery used in the UWM Lab for experimentally demonstrating the mitigation of power variability from renewable energy sources. The battery is rated at 50 kW, 675 Ah and 120 V fully charged, based on the concept proposed by Ahmad Hamidi, 2015.

is impossible to meet the performance and economic requirements for broad market penetration because of mentioned disadvantages.

Zinc Bromine (ZNBR) flow batteries: They are a hybrid Redox flow battery because much of the energy is stored by Plating Zinc metal as a solid on to the anode plates in the electrochemical stack during charge [17]. They offer high cell voltages. Zinc bromide energy storage is proper to use in renewable energy systems. In operating lifetime period, Zinc Bromide energy storage can exceed 2000 fully charge and discharge cycles. It can discharge fully with no damage to the battery. The energy density of this battery is reported around 65-84 Wh/Kg and it can operate at a wide range of temperature with no degradation. This battery can meet the performance and economic requirements for broad market penetration because materials of the component can be made from plastic. Figure 2.12 shows Zinc-Bromide (ZnBr) flow battery used in the UWM Lab.

2.3.3 Flywheels

Flywheels are a rotating mechanical device that is used to store rotational energy [17]. Flywheel energy storage system stored electric energy in the form of kinetic energy which can be described as energy of motion. Flywheels benefit us improving the electric grid current. Its also can catch energy from intermittent energy sources and transfer an uninterrupted power to the grid.

In this type of energy storage system, kinetic energy is stored in a rotating mass which speeds up through an integrated motor-generator with very low friction losses. When



FIGURE 2.13: NASA's 41,000 RPM flywheel battery(www.damninteresting.com/the-mechanical-battery)

kinetic energy draws down in the same motor-generator, the energy is discharged. Most modern high-speed flywheel energy storage systems have a cylinder which is supported on a stator. Flywheel energy storage systems work in a vacuum to decrease drag and increase efficiency. Flywheel energy storage systems benefit us with low maintenance, long life, and negligible environmental impact. Flywheel energy storage systems are highly attractive in high power systems and also they are important for applications which require frequent cycling.

A flywheel battery has energy densities 3-4 times higher than traditional lead-acid, at around 100-130 W.Hr/ k. The energy can store and discharge rapidly with no damage to the battery. It means this type of battery can fully charge in minutes instead of hours and it can deliver up to one hundred times more power to compare with a conventional battery. It can operate in a wide range of temperature since temperature doesn't have any effect on it. It improves efficiency up to 85-95%, and its lifespan is reported in decades rather than years. It uses in power companies for load leveling purposes.

Flywheel systems are developed by NASA recently because the unique advantage of flywheels is providing energy storage and attitude control for a spacecraft or satellite in one easy package. The satellite can maintain its attitude if two flywheels aboard a satellite rotate in opposite directions at the same speed. So the satellite can rotate when energy is transferred among the wheels to speed one and slow the other. Figure Ref Fig: NASA shows NASA's 41,000 RPM flywheel battery.

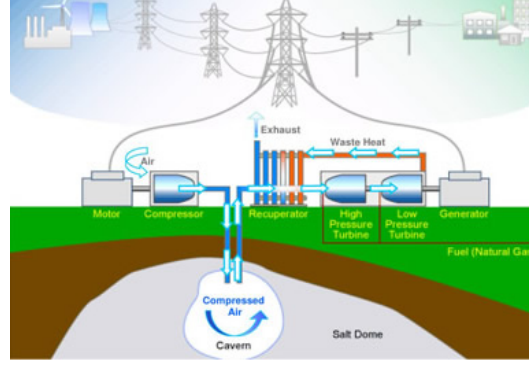


FIGURE 2.14: Compressed Air Energy Storage (CAES) in Salt Caverns. Figure provided by Ridge Energy Storage and Grid Services LP)

2.3.4 Compressed air energy storage

Compressed Air Energy storage is a way to store energy generated at one time for use at another time [17]. It works similar to conventional gas turbine peak-load power plants. In this type of energy storage, compressed air and combustion gas are moved to the combustion chamber directly and higher turbine outputs will transfer to the shafts of the generator. At utility scale, extra generated energy during off-peak demand can be used at period of peak load. CAES provides on-site energy storage solutions with large installations which can store a large amount of energy for the grid. There are three different of Compressed Air Energy storage: Compressed Air Energy storage(CAES), Advanced Adiabatic Compressed Air Energy storage (AA-CAES), and Isothermal Compressed Air Energy storage.

Compressed Air Energy storage (CAES) compresses and stores ambient air under pressure in an underground cavern. In the case of requiring for electricity, a turbine, which drives a generator for power production, spins with heating and expanding the pressurized air. In another way, this type of energy storage has a compressor which pressurizes air and then its pumped into underground geological formations. Salt caverns use as storage tanks. Compressed air is pumped in during the night when the load is low and when the load demand is high, the released air is heated by natural gas to spin a turbine and generate power. Figure 2.14 shows compressed air energy storage in salt caverns.

Advanced Adiabatic Compressed Air Energy storage (AA-CAES) is a progression of traditional CAES since it can deliver compressed air at a higher temperature and higher pressure. It has higher efficiency around 70%. It works similar to traditional CAES but the difference with traditional one is in the handling of the heat of compression. AA-CAES release the heat and store it separately and it causes increasing efficiency.

Isothermal Compressed Air Energy storage tries to overcome some of the limitations of traditional CAES which is removing heat from the air in the compression cycle and

adding heat in the expansion cycle. In Isothermal Compressed Air Energy storage, air can reach to higher pressure with no inherent challenges of high thermal losses or high temperatures. In this type of energy storage, electrical energy can be delivered with no need for natural gas combustion when power is required. Isothermal Compressed Air Energy storage improves compressed air energy storage technology since it doesn't use natural gas and also it improves our environment by reducing natural gas emissions. It is still under study and there isn't any commercial type yet.

2.3.5 Thermal

The energy storage technologies allow us to temporarily reverse energy produced in the form of heat or cold for use at a different time [17] for heating and cooling applications and power generation like solar thermal power plants. For instance, in solar thermal power plants the surplus produced energy is stored in the form of molten salt or other materials. The stored energy can be released by producing steam which rotates a turbine to produce electricity. There are three different types of thermal storage: Pumped Heat electrical Storage (PHES), Hydrogen Electrical Storage, and Liquid Air Electrical Storage.

Pumped Heat electrical Storage (PHES) has two large thermal stores: cold store and hot store. Electricity is stored by pumping heat from the cold store to the hot store and heat. In this process waste heat is delivered to the cold store to produce mechanical work. In the recovering process, a generator is driven by the heat engine. Pumped Heat electrical Storage (PHES) is a low cost energy storage technology, which has a high round trip efficiency around 75-80 %.

In Hydrogen Electrical Storage model electricity is converted into hydrogen by electrolysis and hydrogen is stored. This type of energy storage provides higher storage capacity to compare with batteries, but its efficiency is low like 30-40 %. Because of its low efficiency, it's not highly considered.

Liquid Air Electrical Storage Cool air by using electricity till it liquefies, then liquid air is stored in a tank. Liquid air is brought back to a gaseous state to drive a turbine and produce electricity. LAES provide long-period, twice as long as average battery technology and large scale energy storage. It has high efficiency around 70%.

2.3.6 Pumped hydro power

Gravity is a powerful, inescapable force that surrounds us at all times and it also underpins one of the most established energy storage technologies [17]. As it's mentioned

in hydroelectric chapter, hydroelectric power depends on water falling down through a turbine. There are different ways to store generated electricity by hydroelectric source: : Pumped Hydroelectric Storage, Subsurface Pumped Hydroelectric Storage, Surface Reservoir Pumped Hydroelectric Storage, and Variable Speed Pumped Hydroelectric Storage.

In Pumped Hydroelectric Storage, energy is stored in the form of water in two reservoirs: lower and upper. Water is stored in the upper reservoir during low electricity demand, and it pumps to lower reservoir to generate electricity through turbines during high electricity demand. Pumped Hydroelectric Storage has high efficiency which is greater than 80. It balances the load within the overall power system which is very beneficial and also its highly economical.

In Subsurface Pumped Hydroelectric Storage, the reservoirs are placed underground (sub-surface). This project has yet to be completed. Variable Speed Pumped is proposed pumped storage devices. It consists of two pumps: closed loop and open loop which depend on their connection with rivers. The closed loop model has two reservoirs which are isolated from a free flowing water source while open loop model take free flowing water source for the lower and upper reservoir.

Variable Speed Pumped Hydroelectric Storage modifies the speed to tune the frequency of the electric grid and consequently causes frequency regulation and grid stability. Power consumed can be varied over a range of outputs which ends up improving turbines efficiency. This new technology is helpful to assist, variable renewable energy inputs. A wide operating range is provided by using type of energy storage.

2.4 Application of Energy Storage in Buildings

Growing demand for energy in the world and lack of energy sources are two important reasons that arise worldwide attention searching for suitable green energy sources. The main renewable energy sources for residential and small buildings are solar and wind power which reduces the carbon dioxide emissions and slow down the global temperature increasing. Renewable energy sources are suitable for electricity generation, but they are intermittent and variable. Energy storage technologies can smooth out this variability by allowing unused electricity to be stocked for later use when generation capacity is low to meet demand [18]. Integrating of energy storage in the buildings helps to produce affordable, stable, and sustainable power supply and extended period of access to clean solar or wind power. Also, it benefits us to match the energy supply with demand.

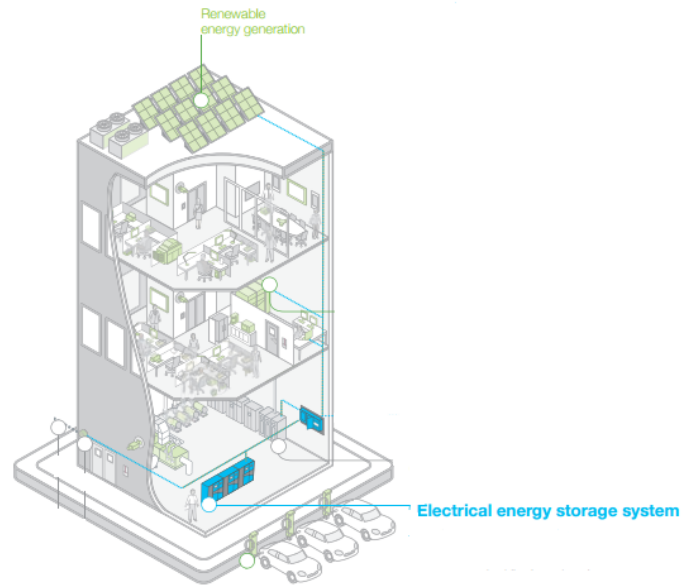


FIGURE 2.15: Integration of renewable energy generation, PV, and electrical energy storage system in an example building. Source: Based on the Concept provided by S. Faias, P. Santos, J. Sousa, R. Castro, International Conference on Renewable Energy and Power Quality, 2008

Figures 2.15 shows a building which is integrated with renewable energy generation, PV, and electrical energy storage system.

As it's explained in energy storage sub-chapter (2-3) there are several energy storage technologies: batteries, flywheels, pumped hydropower, compressed air energy storage, and thermal. In this chapter, we will explain the suitable energy storage systems for residential and small building applications. It is necessary to make a differentiation between short and long-term response energy storage technologies. Long-term response energy storage systems are used to absorb and supply the electrical energy during minutes or hours, they are then able to be used for energy management, frequency regulation and grid congestion management [19] like electrochemical batteries, Redox flow, compressed air, and pumping hydro. Short-term energy storage systems are used in order to increase the power quality and to maintain the voltage stability of power electrical network throughout of an intervention during the transient regime in the range of few seconds to minutes [19].

The most popular energy storage devices are batteries because of their high energy density, high energy capability, high efficiency, cycling capability, life span, and initial cost. There are two different types of battery: electrochemical and Redox flow. Electrochemical batteries store energy in electrochemical form, creating electrically charged ions, the principle of work being based on chemical reactions between positive and negative plates [18]. Direct current is converted into chemical energy during charge period and the chemical energy is converted back into a flow of electrons in the direct current form

TABLE 2.1: Comparison of zinc bromide energy storage with other batteries. Based on the concept proposed by Emad Manla, IEEE Transaction, 2010.

| | Energy Density (Wh/Kg) | Power Density (W/Kg) | Cycle Life |
|----------------------|---------------------------|-------------------------|------------|
| Lead-Acid | 30-50 | 100-2000 | 200-300 |
| Lithium-Ion | 150-190 | 300 to 1500 | 300-500 |
| Nickle Metal Hydrate | 60-120 | 250-1000 | 300-500 |
| Zinc Bromide | 85-90 | 300-600 | 2000 |

during discharge period. There are several electrochemical battery technologies which can be considered as an energy storage, for instance: Lead-acid, Nickel metal hydrate, Zinc bromide, Lithium ion.

Lead-acid batteries are suitable for using in vehicles and in stationary equipment. The higher energy density capability of lead-acid batteries is 30 to 50 Wh/Kg. But they are not cost effective for higher power applications. Lithium-ion batteries are more proper for electric vehicle applications because high energy density can offset the higher cost of this type of battery. Lead-acid, Lithium-Ion, and Nickel metal hydrate batteries all have a short cycle of life so it is not recommended to fully discharge. Because of this disadvantage we need to install a larger battery bank, which will be so expensive. The zinc bromide batteries can exceed 2000 full charge and Discharge cycles during its operating lifetime without any damage compared with 750 cycles for conventional lead acid batteries. Also, they can operate at a different operating temperature without degradation. The materials of the components can be made entirely with plastic to reduce costs and provide readily for recycling or disposal. In addition, it uses a low-toxicity electrolyte and recyclable plastic battery stacks compared with more toxic lead and sulfuric acid [20]. They have a cycle life of 2000 which can be fully charged and discharged repeatedly without any damage. So they approach three times the average cycle life of the lead acid batteries. Zinc bromide batteries are suitable for applications which need the deep - cycling capability and long cycle life.

Table 2.1 shows the comparison of zinc bromide energy storage with other batteries.

Chapter 3

Modeling of Building Energy System Using Energyplus Software

3.1 Energyplus Overview

In 1995, the U.S. Department of Energy (DOE) started to create a new building simulation tool to reach to two targets as below:

- Develop existing tool according to users recommendations.
- Define a new simulation program is called EnergyPlus.

EnergyPlus is a simulation program designed for modeling buildings with all their associated heating, ventilating, and air conditioning equipment. EnergyPlus is a simulation engine: it was designed to be an element within a system of programs that would include a graphical user interface to describe the building. However, it can be run stand alone without such an interface [21]. EnergyPlus has its roots in both the BLAST and DOE2 programs. BLAST (Building Loads Analysis and System Thermodynamics) and DOE2 were both developed and released in the late 1970s and early 1980s as energy and load simulation tools [21]. To make EnergyPlus well-organized and modular structure, Fortran 90 Was selected as the programming language since it have several advantages such as:

- Its a modular language.

- It mixes language modules.
- It is object based.
- Long variable names can be selected by this programming language.
- During the development process, it provides backward compatibility.

EnergyPlus is a program that can analysis, energy and thermal load in buildings. The goals of this program are sizing appropriate HVAC equipment, cost and energy analysis, optimizing energy performance, and etc. EnergyPlus will calculate the heating and cooling loads necessary to maintain thermal control set-points, conditions throughout a secondary HVAC system and coil loads, and the energy consumption of primary plant equipment as well as many other simulation details that are necessary to verify that the simulation is performed as the actual building would [21].

EnergyPlus is modular so its possible to develop modules concurrently without interfering with other modules and also its easier to form links with other programming elements. Modularity of EnergyPlus makes it developer friendly. Figure 3.1 An EnergyPlus structure which integrated solution manager manages the surface and air heat balance modules and works between the heat balance and the building systems simulation manager as an interface. Inside and outside surface heat interconnections between heat balances and boundary conditions, conduction, convection, radiation, and mass transfer effects are done by the Surface Heat Balance Module. The Air Mass Balance Module works with various mass streams such as exhaust air, ventilation air, and infiltration. All these program modules work together to calculate the required energy for heating and cooling a building.

Figure 3.2 shows Energyplus is the integration of Integration of Loads, Systems, and Plants. It also shows EnergyPlus has three basic components: a Simulation Manager, a Heat and Mass Balance Simulation module, and a new Building Systems Simulation module. Communication between the heat balance engine, air loops, the HVAC, water, and their attached components are handled by the Building Systems Simulation. Data communication management between HVAC modules, input data, and output data also is done by by the Building Systems Simulation. Integration of Loads, Systems, and Plants in EnergyPlus provides a better understanding of how a building responds not only to the environmental factors that impact the building but also the HVAC system as it attempts to meet the thermal loads on the building [21].

Another advantage of EnergyPlus is it's open source code. So it allows many developers to work on the program to improve accuracy and usability of the program.

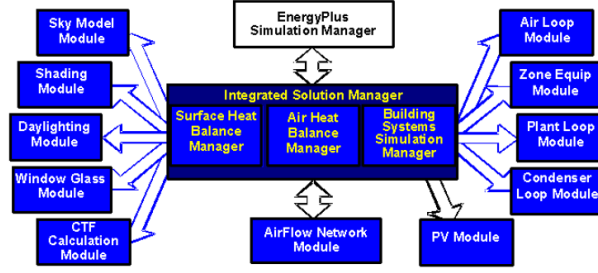


FIGURE 3.1: EnergyPlus Program Schematic and internal elements. Picture provided by U.S. department of energy.

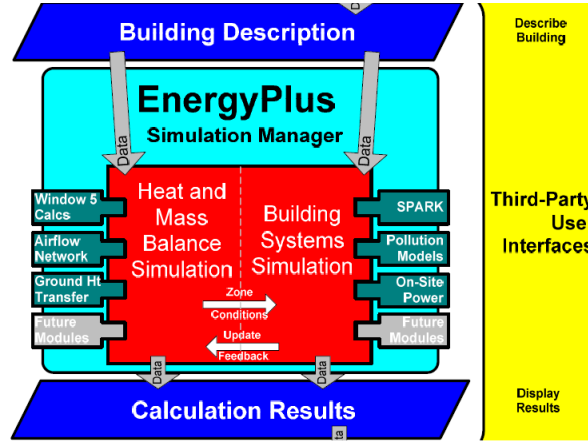


FIGURE 3.2: Overall EnergyPlus Structure. Picture provided by U.S. department of energy.

In summary, EnergyPlus aims to be a program that is relatively simple to work with from the perspective of both the users and the developer. The development team made tremendous efforts to keep simulation code, and algorithms as separate as possible and as modular as possible to minimize the overall knowledge that someone would need to have to add models to the program. This will minimize the resource investment and maximize the impact of current research in the field of building energy analysis and thermal load calculations [21].

3.2 Energyplus Input and Output

For easy maintenance and expansion in EnergyPlus, input and output data files are designed instead of user readability. EnergyPlus includes various input files (IDF files) to explain the building to be modeled, and also it includes the environment surrounding information. EnergyPlus has several output files which process further to be understandable results of the simulation. The input data file is the primary file that EnergyPlus uses to create the building simulation [21]. The input is order-independent; data can appear in any order and will be retrieved and sorted as necessary by the EnergyPlus

simulation modules. In addition, EnergyPlus allocates everything dynamically, so there are no limitations as to the number of zones, surfaces, etc. [21]. EnergyPlus reads the data dictionary (Energy+.idd) and the input data file (in.idf) prior to doing anything else. Only after this is done does processing start. However, the input processor only knows as much as the data dictionary has told it. It knows which fields should be the alpha and which should be numeric [21]. As its mentioned, EnergyPlus has a modular structure. So each module gets its own input from the input processor in the form of numeric and alpha fields. EnergyPlus input file doesnt work as the main interface for typical end-users. A third-party developer acts as an interface between EnergyPlus and users.

The primary file that creates the building simulation in EnergyPlus is an input data file. In Energyplus there no limitations for number of surfaces, zones, and There are some general rules related to EnergyPlus input data files like:

- Each line should start with a comma or semicolon.
- Blank lines are acceptable.
- Input line length cant be more than 500 characters.
- Alpha string length can be 100 characters and it must be in upper case.
- Some special characters cannot be used in the file like tabs.
- Numbers can be entered in different way like 1.0, 1.000, 0.1E+1 which are all equally processed.

Weather data is another major input data in EnergyPlus. Its a simple text-based format file like input and output data. Weather data file includes key information about a location in the first eight lines such as: data source, latitude, longitude, time zone, location, elevation, peak heating and cooling design conditions, typical and extreme periods, holidays, daylight savings period, and period covered by the data.

EnergyPlus saves summary or detail level reports in an output data file for each time step during a simulation. The output results are processed in a simple variable-based format which is readable by post-processing programs. EnergyPlus output reports can be viewed in spreadsheet format or other software which can process delimited variable reports. An EnergyPlus output file can have four different extensions as below:

- Tab: Tabs are used in reports with a tab extension to indicate the beginning or end of a character string.

TABLE 3.1: EnergyPlus Inputs and Outputs.

| EnergyPlus Inputs | EnergyPlus Outputs |
|---|---|
| Simulation parameters | Total used energy |
| Location and climate | Total electricity |
| Schedules | Electric load satisfy hours |
| Surface construction elements | Electricity coming from utility |
| Thermal zone surface | Electricity going to utility |
| Internal gain | Water supplied by utility |
| Air flow calculation method | Information on all zones |
| Exterior equipment | Not meet hours set point hours |
| HVAC parameters | Interior lighting density for each zone |
| Fans parameters | Zone cooling and heating output |
| Coils parameters | Shadowing summary |
| Pumps | Number of objects |
| Solar collector | Annual, max, min value of electricity and gas |
| Water heaters and thermal storage | Energy generated by PV and Wind |
| Set-points manager | Produced electric power by PV |
| Electric load center like battery, generator, Pv , wind and etc | Inverters Dc input/ Ac output electric power |
| Water system | Battery charge / discharge energy/ power |
| performance curves | Total purchase/ produced/ demand electric power |
| Performance tables | Total HVAC electric demand power |
| Economies | Construction cost summary |

- Csv: Commas are used in reports with a .csv extension to indicate the beginning or end of a character string. These are provided reports in spreadsheets.
- Txt: Spaces are used in reports with a .txt extension to indicate the beginning or end of a character string.
- Html: Reports with .html extension provide output reports in web-browser.

Table 3.1 shows a list of EnergyPlus inputs and outputs.

In summary, input, output, and weather files, which associated with EnergyPlus, all are easy to read and explain by other programs like databases, spreadsheets, or custom programs. These files can be used by other building design program, if EnergyPlus works with third party developer.

We don't need to work with all of these inputs. For this project we want to add Zinc bromide battery specifications in EnergyPlus. So we need to know about EnergyPlus kinetic battery inputs and outputs. Table 3.2 shows EnergyPlus inputs with a short description of each one.

Table 3.3 shows EnergyPlus outputs with a short description of each one.

3.3 EP-Launch and IDF Editor

This section will explain the EP-Launch program, which helps you run EnergyPlus.

TABLE 3.2: EnergyPlus Kinetic battery Inputs .

| Output fields | Description |
|--|---|
| Electrical storage mode of operation | Idle:0,Dis: 1, Ch.:2 |
| Electrical storage SOC (Ah) | Stored charge in the battery at any a point of time |
| Electrical storage fraction SOC | Ratio between ES SOC and max capacity |
| Electrical storage | Storage losses fraction |
| Electrical storage Power (W)/ Energy (J) in to storage | Total power/energy fed in to the battery |
| Electrical storage power (W)/ Energy (J) from storage | Total power/energy drawn from the battery |
| Electrical storage total current (A) | Current to(Ch. negative)/from (Dis. positive) the battery |
| Electrical storage total voltage (V) | Total terminal voltage of the battery |
| Electrical storage thermal loss power/energy | Thermal loss power/energy in Ch./Dis. |
| Electrical storage fraction damage | Battery life fraction |

TABLE 3.3: EnergyPlus Kinetic battery Inputs .

| Input fields | Description |
|---|--|
| Name | Battery bank name |
| Availability schedule name | Greater than 0 when battery is available |
| Zone name | Thermal zone name |
| Radiative fraction | Storage losses fraction |
| Num. of battery modules in parallel | Num. of battery connected in parallel |
| Num. of battery modules in series | Num. of battery connected in series |
| Max module capacity | Battery max capacity in Ahr |
| Initial fraction state of charge | Initial SOC |
| Fraction of available charge capacity | Total charge fraction in available tank |
| Ch. rate from bound ch. to available charge | The rate that Ch. flows between two tanks |
| Fully charged battery OCV | OCV for fully Ch. |
| Fully Dis. battery OCV | OCV for fully Dis. |
| Voltage change curve name for ch. | Rectangular hyperbola type 2 in Ch. |
| Voltage change curve name for Dis. | Rectangular hyperbola type 2 in Dis. |
| Internal electric resistance | Internal resistance in Ohms |
| Max Dis. current | Max current which battery can Dis. continuously |
| Cut off voltage | Min allowable voltage |
| Charge rate limit | Min charge current |
| Battery life calculation | It shows if the battery life model is activated or not |
| Num. of cycle bins | Num. of cycle bins in battery life simulation |
| Battery cycle life curve name | It correlates the cycles of battery failure and fractional depth of Dis. |

EP-Launch works like a standard Windows program. EP-Launch is windows installation and it cant install on Linux and Mac platforms. EP-Launch provides an easy way to select a file and run it in EnergyPlus. Figure 3.4 shows EP-Launch screen. EP-Launch can access easily to other programs and help us not to work with DOS command line prompt to run EnergyPlus. There is a single input file tab for input file and weather files in this program which allows us to select an input file and weather file. Also, we can choose a group of input files in the EP - Launch. We can choose input file and weather file through the File tab in EP-Launch also.

Furthermore, EP-Launch has several choices for output files which can we choose like a spreadsheet, web browser, HTML, and drawing files. Also, there is a tab which is called All that provides us to choose a special output file like error file, variable file, and etc. Figure 3.3 shows this. Some important output files are:

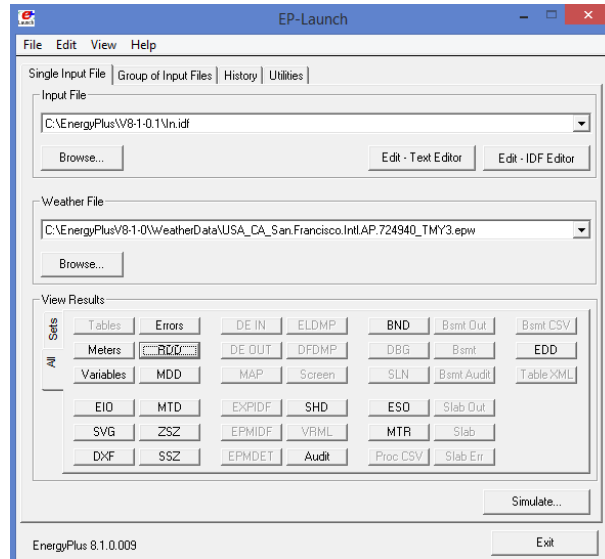


FIGURE 3.3: EP-Launch different output file options. Picture captured from EnergyPlus software.

- Errors: List of errors and warnings.
- Meters: Tabulated meter report.
- RDD: List of output variables from the run.
- Variables: Tabulated results in comma, tab or space.
- MDD: List of output meters available from the run.
- MTD: list of meter component variable.
- SVG: HVAC Diagram.
- ZSZ: Zone sizing details.
- DXF: Drawing file in AutoCAD DXF format.
- SSZ: System sizing details.
- SHD: Shading output.
- Audit: Input file echo with input processor errors and warnings.
- BND: Details of HVAC system node and component connection.
- ESO: Raw report variable output.
- MTR: Raw report meter output.
- EDD: Details of Energy Management System.

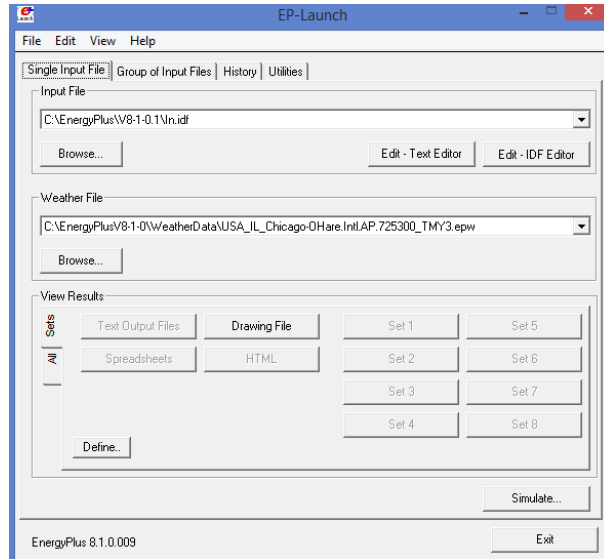


FIGURE 3.4: EP-Launch screen. Picture captured from EnergyPlus software.

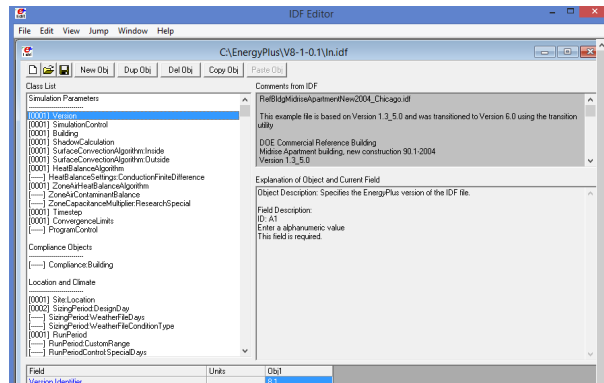


FIGURE 3.5: IDF Editor screen. Picture captured from EnergyPlus software.

In Ep-Launch View tab provides another way to choose an output file type report. Help tab provides an access to EnergyPlus documents.

There are two different editors in EP-Launch: Text editor and IDF editor which allows us to open a text editor for input files and make some changes in input files. IDF Editor is a simple way to create or edit EnergyPlus input data files. On the other way, the IDF Editor is a simple, intelligent editor that reads the EnergyPlus Data Dictionary (IDD) and allows creation/revision of EnergyPlus Input Files (IDF). It can be run from a shortcut in the main EnergyPlus directory (created as part of the install) or directly from EP-Launch [21]. Figure 3.5 shows Idf Editor screen.

IDF Editor works in conjunction with the current EnergyPlus Input Data Directory (IDD) file that resides in the directory where EnergyPlus is installed [21].

Required items for this project are listed as below:

TABLE 3.4: curve RectangularHyperbola2 Input Data.

| Field | Description |
|--------------------|---|
| Name | Defining charge or discharge curve |
| Coefficient 1, C1 | Coefficient C in kinetic battery OCV formula |
| Coefficient 2, C2 | Coefficient D in kinetic battery OCV formula |
| Coefficient 3, C3 | Coefficient A in kinetic battery OCV formula |
| Minimum value of X | battery charge divided by the maximum capacity at a given current |
| Maximum value of X | Total power/battery charge divided by the maximum capacity at a given current |

- Performance Curves/ curve: RectangularHyperbola2.
- Generator: Photo voltaic.
- Photo voltaic Performance; Simple.
- Electric Load Center: Inverter: Look Up Table.
- Electric Load Center: Storage: Battery.
- Electric Load Center: Distribution.
- Energy Management System: Sensor.
- Energy Management System: Actuator.
- Energy Management System: Program.
- Energy Management System: Global Variable.
- Energy Management System: Output Variable.
- Energy Management System: Trend Variable.
- External Interface.
- External Interface: Schedule.
- External Interface: Variable.

3.3.1 Performance Curves/ curve: RectangularHyperbola2

In this field we should determine six essential variables to determine the change of open circuit voltage as a function of the battery state of charge of charging. The change of open circuit voltage is relative to a fully discharged battery. Table 3.4 shows the input data for this object.

TABLE 3.5: Photo voltaic Input Data.

| Field | Description |
|---------------------------------------|---|
| Name | Unique name for the PV array |
| Surface Name | Name of surface |
| Photo voltaic Performance Object Type | PV performance model |
| Heat Transfer Integration Mode | Integrating model with other EP heat transfer surfaces |
| Module Performance Name | Name of the PV performance |
| Number of Series Strings in Parallel | # of series strings of PV modules that are in parallel to form the PV array |
| Number of Modules in Series | The number of modules wired in series to form the PV array. |

TABLE 3.6: Photo voltaic Performance Input Data.

| Field | Description |
|--|---|
| Name | The name of the PV array |
| Fraction of Surface Area with Active Solar Cells | Fraction for the area of surface |
| Conversion Efficiency Input Mode | How the PV array efficiency values are input |
| Value for Cell Efficiency if Fixed | The efficiency of solar incident energy conversion to electricity |

3.3.2 Generator: Photo voltaic

This object determines description of an PV modules' array and how they are to be modeled. Table 3.5 shows input data for this object.

3.3.3 Photo voltaic Performance; Simple

It describes a simple model of photo voltaic that may be useful for early phase design analysis. Table 3.6 shows input data for this object.

3.3.4 Electric Load Center: Inverter: Look Up Table

We can model conversion from Direct Current (DC) to Alternating Current (AC) with this object in an electrical load center that contains a photo voltaic modules. Load center should have an array of photo voltaic modules to feed an inverter DC power to produce AC power with the inverter. This input object is for an inverter model where efficiency is interpolated using a look up table. Table 3.7 shows the input data for this object.

3.3.5 Electric Load Center: Storage: Battery

The kinetic battery model (KiBaM) is used for this object to simulate rechargeable battery banks in an electrical load center. Voltage, current, and energy losses can be modeled by this object with charging and discharging during each time step. The cumulative battery damage can be also modeled and reported at the end of each simulation run. Table ?? shows the input data for this object.

TABLE 3.7: Inverter Look Up Table Input Data.

| Field | Description |
|--|--|
| Name | Unique name for the inverter |
| Availability Schedule Name | The name of a schedule that describes when the inverter is available |
| Radiative Fraction | The fraction of inverter thermal losses |
| Rated Maximum Continuous Output Power | The rated maximum continuous output power in watts |
| Night Tare Loss Power | Night tare loss in watts |
| Nominal Voltage Input | The nominal DC input voltage in volts |
| Efficiency at 10% Power and Nominal Voltage | The fractional efficiency at nominal voltage and 10% power |
| Efficiency at 20% Power and Nominal Voltage | The fractional efficiency at nominal voltage and 20% power |
| Efficiency at 30% Power and Nominal Voltage | The fractional efficiency at nominal voltage and 30% power |
| Efficiency at 50% Power and Nominal Voltage | The fractional efficiency at nominal voltage and 50% power |
| Efficiency at 75% Power and Nominal Voltage | The fractional efficiency at nominal voltage and 75% power |
| Efficiency at 100% Power and Nominal Voltage | The fractional efficiency at nominal voltage and 100% power |

TABLE 3.8: Battery Input Data.

| Field | Description |
|---|---|
| Name | Name for the battery bank |
| Availability Schedule Name | The battery availability |
| Radiative Fraction | The fraction of storage losses |
| Number of Battery Modules in Parallel | # of modules connected in parallel |
| Number of Battery Modules in Series | # of modules connected in series |
| Maximum Module Capacity | The maximum capacity of battery |
| Initial Fractional State of Charge | The initial state of charge |
| Fraction of Available Charge Capacity | Available charge capacity to total cap |
| Change Rate from Bound Charge to Available Charge | Charge flow rate between 2 tanks |
| Fully Charged Module Open Circuit Voltage | The open circuit voltage for a fully charged |
| Fully Discharged Module Open Circuit Voltage | The open circuit voltage for a fully discharged |
| Voltage Change Curve Name for Charging | Change of OCV as a function of the SOC in charging |
| Voltage Change Curve Name for Discharging | Change of OCV as a function of the SOC in discharging |
| Module Internal Electrical Resistance | The battery internal resistance |
| Maximum Module Discharging Current | Max current that battery can discharge |
| Module Cut-off Voltage | The minimum allowable voltage |
| Module Charge Rate Limit | Charging current limitation |
| Battery Life Calculation | The battery life model |
| Number of Cycle Bins | # of equally ranged cycle bins in battery life simulation |
| Battery Cycle Life Curve Name | The name of a double exponential decay curve |

TABLE 3.9: Distribution Input Data.

| Field | Description |
|---|--|
| Name | Name for the electric load center |
| Generator List Name | Name for the list of generators |
| Generator Operation Scheme Type | The type of operating scheme for the generator set |
| Demand Limit Scheme Purchased Electric Demand Limit | The user input for the demand limit |
| Electrical Buss Type | Electric load center configuration |
| Inverter Object Name | The inverter name connected to load center |
| Transformer Object Name | Transformer connected to this load center |

3.3.6 Electric Load Center: Distribution

ElectricLoadCenter: Distribution objects are used to define on-site electricity generators in an EnergyPlus simulation. It reports the amount of electricity generated and purchased. Table 3.9 shows the input data for this object.

TABLE 3.10: EMS Sensor Input Data.

| Field | Description |
|--|---|
| Name | Unique name for the sensor |
| Output:Variable or Output:Meter Index Key Name | Key reference for the specified output variable |
| Output:Variable or Output:Meter Name | The name of the output variable or meter |

TABLE 3.11: EMS Actuator Input Data.

| Field | Description |
|---------------------------------|--|
| Name | Unique name for the actuator |
| Actuated Component Unique Name | Unique name for the specific entity that is to be controlled |
| Actuated Component Type | The type of the entity that is to be controlled by the actuator |
| Actuated Component Control Type | the type of control to be done on the specific entity being controlled |

TABLE 3.12: EMS Program Input Data.

| Field | Description |
|----------------------|---|
| Name | The unique name of the Erl program |
| Program lines 1 to N | A single line of code for the EnergyPlus Runtime Language |

3.3.7 Energy Management System: Sensor

It declares an Erl variable that is linked to EnergyPlus output variables or meters. Information from elsewhere is gotten by this object in the model for use in control calculations. The separate output files called eplusout.rdd and eplusout.mdd provide a listing of the output variables and meters that can be used as sensors. Table 3.10 shows input data for this object.

3.3.8 Energy Management System: Actuator

An Erl variable to a control actuator elsewhere is mapped by this object in EnergyPlus. The EMS changes the value of this variable in an Erl program to initiate control actions. The eplusout.EDD file can contain a listing of the actuators available for a specific model. Table 3.11 shows the input data for this object.

3.3.9 Energy Management System: Program

It is the central processor of the EMS and the primary container for the EnergyPlus Runtime Language, or Erl. Table 3.12 shows the input data for this object.

3.3.10 Energy Management System: Global Variable

One or more global variables that can be accessed by all Erl programs in the EMS is declared by this object. User declares Erl variables as sensor and actuators objects are

TABLE 3.13: EMS Global Variable Input Data.

| Field | Description |
|--------------------------|------------------------------|
| Erl Variable (1..N) Name | The global Erl variable name |

TABLE 3.14: EMS Output Variable Input Data.

| Field | Description |
|--------------------------|--|
| Name | User-defined name for the new output variable |
| EMS Variable Name | EMS variable name that is to be mapped to the custom output variable |
| Type of Data in Variable | The nature of the variable |
| Update Frequency | Which time step the variable is associated with |

TABLE 3.15: EMS Trend Variable Input Data.

| Field | Description |
|-----------------------------------|--|
| Name | Global EMS trend variable name |
| EMS Variable Name | The EMS variable name that is to be mapped to the trend variable |
| Number of Time steps to be Logged | How much data are to be held in the trend variable |

already global variables. Global scope variables are required to move data in and out of subroutines. Table 3.13 shows the input data for this object.

3.3.11 Energy Management System: Output Variable

A custom output variable that is mapped to an EMS variable is created by this object. Data from an Erl program can be obtained from this and it is essential for developing and debugging programs. This object also helps to create custom output variables by a powerful mechanism. Table 3.14 shows the input data for this object.

3.3.12 Energy Management System: Trend Variable

A global trend EMS variable is declared by this object that can be accessed by all Erl programs in the EMS. The recent history of the Erl variable can be stored by this object. The trend data are required for the progression examination of time series data. Trend data are saved in a stack so that the most recent data are at the beginning of the stack. Table 3.15 shows the input data for this object.

3.3.13 External Interface

This object activates the external interface of EnergyPlus. If it is activated, then the external interface object values will receive from the BCVTB interface or from FMUs at each zone time step. Otherwise the its values will be fixed with the initial value field of the corresponding object. Table 3.16 shows the input data for this object.

TABLE 3.16: External Interface Input Data.

| Field | Description |
|-------|--------------------------------|
| Name | Name of the external interface |

TABLE 3.17: External Interface Schedule Input Data.

| Field | Description |
|---------------------------|---|
| Name | Schedule name |
| Schedule Type Limits Name | Reference to the Schedule Type Limits object |
| Initial Value | Schedule value using during the warm-up period and during the system sizing |

TABLE 3.18: External Interface Variable Input Data.

| Field | Description |
|---------------|--|
| Name | The global Erl variable name |
| Initial Value | Initial value using during the warm-up period and during the system sizing |

3.3.14 External Interface: Schedule

Its value is set to the value received from the external interface during the time stepping. Its value is set to the value specified by the field initial value during the warm-up period and the system sizing. Table 3.17 shows the input data for this object.

3.3.15 External Interface: Variable

This input object is similar to EMS Global Variable. Its value is set to the value received from the external interface during the time stepping while it's set to the value specified by the field initial value during the warm-up period. Data can move into Erl subroutines by using this object. Table 3.18 shows the input data for this object.

3.4 Example of Building Modeling

There are several example files in EnergyPlus which you can find inside EnergyPlus Example Files. You can run all files with input data file (idf) extension. In addition, there are two spread sheet, Example files and Example files-objects link, that you can find out some information about example files in Example files spreadsheet, and also you can find out which objects are defined for specific example file in Example files-objects link spread sheet.

To run an example file you should first select the file and weather file in EP-Launch and then press simulate button. To see the output results, you can choose the format in EP-Launch and press that format button. Also, you can make some changes in IDF Editor or you can just get some information about that building. In addition, in class

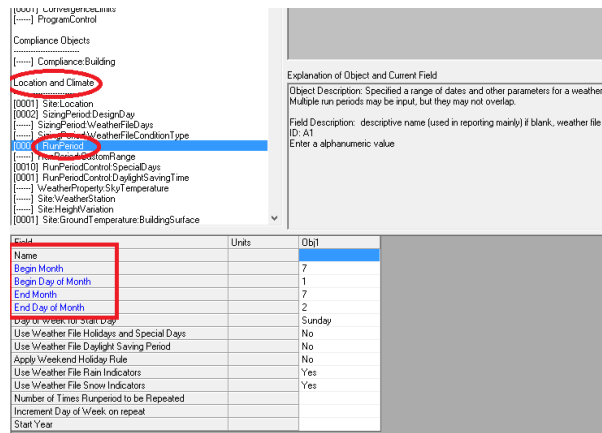


FIGURE 3.6: Defining Run period in IDF Editor.

Timestamp: 2015-06-09 19:18:13

Values gathered over 48.00 hours

WARNING: THE REPORT DOES NOT REPRESENT A FULL ANNUAL SIMULATION.

Site and Source Energy

| | Total Energy [GJ] | Energy Per Total Building Area [MJ/m2] | Energy Per Conditioned Building Area [MJ/m2] |
|---------------------|-------------------|--|--|
| Total Site Energy | 0.76 | 1.94 | 1.94 |
| Net Site Energy | -0.3 | -0.9 | -0.9 |
| Total Source Energy | 0.04 | 0.11 | 0.11 |
| Net Source Energy | -1.4 | -3.6 | -3.6 |

FIGURE 3.7: Total site energy for a shop with PV.

list you can find out which objects has been defined in the example building. In class list, the objects that have a number on left side define objects.

In this part, we ran two example files for 48 hours, which is called shop with simple PV and shop with PV and battery. To define running time for an example in EnergyPlus, we should use IDF editor location and climate class list, run period section. Then we should define begin and end of day and month. Figure 3.7 shows the window.

The shop is a one story building divided into four exterior and one interior conditioned zones. It is a small service repair shop which opens Monday to Friday, 45 hours a week. It has a PV roof surface and a PV collector array. We selected Chicago-Ohare weather file and then run it. The HTML report format was selected since it's tabular. We compared site energy for both examples. First, site energy is the amount of energy which brings to the site like our home. In the first case, shop with PV and no battery, total site energy is 0.76 GJ while it's 0.63 GJ for the second case, Shop with PV and battery. This shows when we use battery we need less energy since we can store energy when the load demand is low and also when power generation is more than what we need. So according to these two examples, using battery in buildings integrated with renewable energy system helps us to save energy and money. Figure 3.7 and Figure 3.8 show total site energy in EnergyPlus the output file.

Values gathered over 48.00 hours

WARNING: THE REPORT DOES NOT REPRESENT A FULL ANNUAL SIMULATION.

Site and Source Energy

| | Total Energy [GJ] | Energy Per Total Building Area [MJ/m2] | Energy Per Conditioned Building Area [MJ/m2] |
|---------------------|-------------------|--|--|
| Total Site Energy | 0.63 | 1.60 | 1.60 |
| Net Site Energy | -4.9 | -4.7 | -4.7 |
| Total Source Energy | 0.04 | 0.11 | 0.11 |
| Net Source Energy | -7.0 | -17.9 | -17.9 |

FIGURE 3.8: Total site energy for a shop with PV and Battery.

In the output file you can see very detailed results like how much power/energy PV produced in every month in one year, how much energy/power battery charge/ discharge in every month, how much energy each zones used, shading summery, HVAC summary, total site energy, climate data summary, equipment summary, and etc. Also you can see energy consumption according to different end user categories.

Chapter 4

Modeling of Energy Storage Components and Systems Using Matlab and Energyplus

4.1 Zinc Bromide Battery Parameters and Matlab Simulink Model

zinc bromide energy storage devices have two types: flowing electrolyte battery and non flow electrolyte Battery. Flowing electrolyte battery that is generally suitable for large-scale power utility, vehicular, and industrial applications with energy storage requirement of 50 kWh and above. The other type, non flow electrolyte battery, which is a natural evolution of the flow battery system for small-scale applications of only a few kilowatt-hour storage [22].

The zinc bromide battery can exceed 2000 full charge and discharge cycles during its operating lifetime compared with 750 cycles for conventional lead acid batteries. It is capable of full discharge (100 percent of stored energy) without any damage to the battery. Its energy density is in the range of 6584W h/kg, and it can operate at a wide range of operating temperature without degradation [23].

As shown in figure 4.1, zinc is electrochemically plated on the smooth anode side of the electrode. Bromine is produced at the cathode along with free electrons. The quaternary salts immediately complex the bromine and form a dense immiscible polybromide liquid which is flushed from the battery by the flowing electrolyte and settles to the bottom of the catholyte reservoir, completing the charging process. During discharge, the polybromide liquid is then returned to the battery cell stacks via a secondary pump

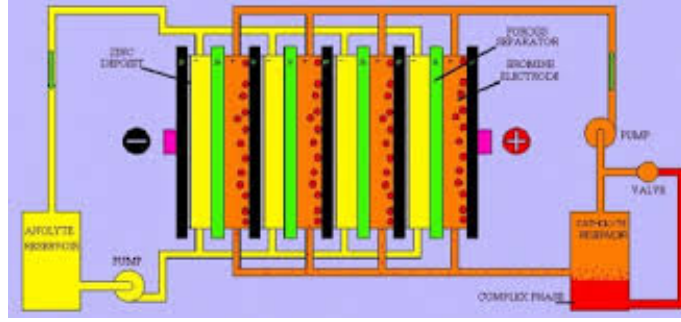


FIGURE 4.1: Zinc bromide energy storage system electrolyte flow. Based on the concept proposed by Emad Manla, IEEE Transaction, 2010.

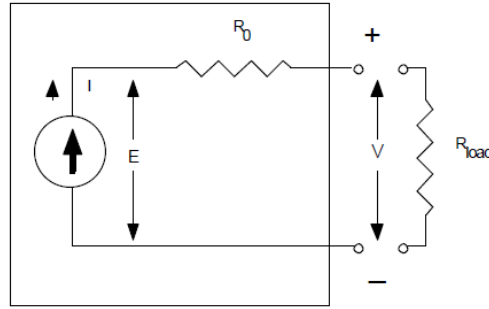


FIGURE 4.2: ZESS electrical equivalent model. Based on the concept proposed by Emad Manla, IEEE Transaction, 2010.

that pulls the dense liquid from the reservoir bottom. At complete discharge, the poly-bromide complex returns to solution ($\text{ZnBr}_2 + \text{H}_2\text{O}$) and quaternary ammonium salts; zinc is oxidized to zinc ions, and bromine is reduced to bromide ions [22].

State of charge (SOC) considers as an important technical term for the battery storage systems which is defined as below:

$$\text{State of charge}(\%) = \frac{\text{Remaining Charge}(A.h)}{\text{Nominal capacity}(A.h)} * 100\% \quad (4.1)$$

In the study case in this project, the zinc energy storage system (ZESS) has a nominal capacity of 675 Ah, nominal open-circuit voltage (OCV) of 120 V at the nominal capacity rated, terminal voltage of 120 when fully charged, and 60 V at fully discharged.

Designed electrical equivalent circuit for this ZESS includes Internal resistance, OCV, and terminal voltage. Figure 4.2 shows ZESS electrical model.

To develop and simulate this equivalent electrical model, several tests has been done on a 50kWh-Zinc Energy Storage System (ZESS) manufactured by ZBB Energy Corporation. So test results help us to estimate electrical parameters of the model.

Many tests have been performed on this energy storage device at various charging and discharging rates, such as 30A, 80A, 150A, and 300A. In each of these tests, the ZESS was charged from an SOC of zero until it reached its full capacity of 675 Ah. Discharging was performed in a slightly more careful way than charging. Namely, discharging began at full SOC, corresponding to full capacity at 675Ah, until the devices terminal voltage reached 60V. Below this voltage level, the ZESS can not establish the demanded current from the load. The ZESS, however, can be discharged at lower currents. The SOC at 60Volts, at any discharging current, is not 0%, as there is still some energy remaining in the ZESS. This energy can be extracted from the ZESS at slower rates down to 20V. Therefore, the ZESS was discharged at a relatively low discharging current rate, 30A, until its terminal voltage reached very low values indicating no remaining charge. This task was performed in order to set it up for the other charging tests that should also start from zero SOC [22].

SOC is calculated based on equation 4.2 in this test:

$$SOC(t) = SOC(0) + \sum_{i=1} I(t_i) * \Delta t_i \quad (4.2)$$

SOC(0) is the initial SOC, $I(t_i)$ is the current rate and Δt_i is the time interval during which the current rate is $I(t_i)$ [22]. In our test $I(t_i)$ consider always constant. In charging mode, it's negative while during discharging mode it's positive.

Battery's cell and ambient temperatures have a significant effect on battery, so the tests have been done under constant cell temperature almost 20 degree Celsius. This means that the factor of temperature is neglected in the process of developing the electrical equivalent model [22]. The test results were documented noting measurements for terminal voltage, SOC, temperature, Open-Circuit Voltage OCV and sampling frequency. The process of charging/discharging was interrupted periodically to measure the OCV. The OCV was measured after the energy storage system had rested from being latively small period of time long enough for the OCV to reach its steady state value at different values of SOC. Towards the end of the discharging period the energy storage device requires a longer time to reach its steady state OCV value [22].

OCV and internal resistance equations have been obtained from test results which are essential to simulate ZESS in Matlab simulation.

Relationship between the OCV and SOC is very significant to model the battery. The OCV was measured at several values of SOC. By plotting OCV versus SOC, it has been noticed that OCV converges to the same value at each particular value of SOC

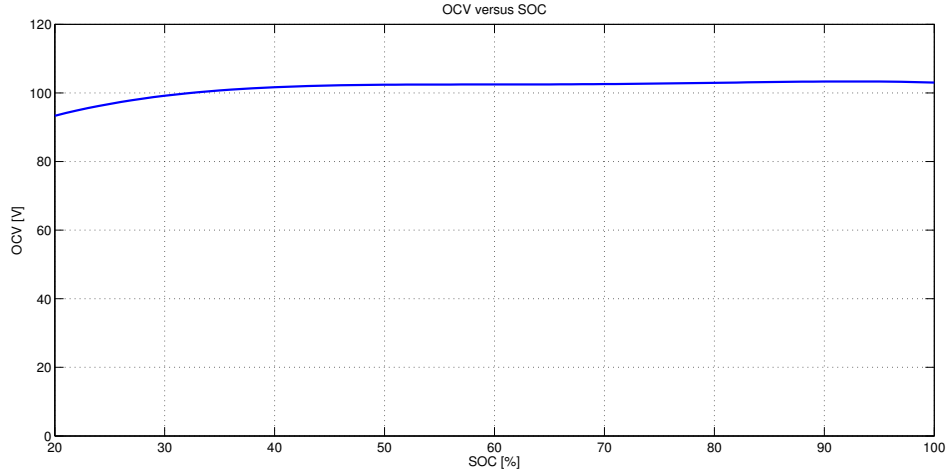


FIGURE 4.3: Zinc Bromide Battery OCV versus SOC.

regardless of the current drawn while testing the ZESS [22]. Different OCV versus SOC curves obtained out of different tests. Then Curve fitting toolbox in Matlab gives a proper relationship between OCV and SOC. In the ZESS case a fourth-degree polynomial function has been obtained [22].

$$OCV = -1.9 \times 10^{-6}(SOC)^4 + 5.3 \times 10^{-4}(SOC)^3 - 0.054(SOC)^2 + 2.4(SOC) + 63 \quad (4.3)$$

This equation shows at SOC equal to zero, OCV is equal to 63v which agrees with the battery's manufacture design. Furthermore, operating the ZESS below an SOC of 20% is not healthy for the battery. Therefore, it is safe to stop utilizing the battery when it reaches this point [22]. Figure 4.22 shows OCV and SOC interpolating polynomial curve.

Another vital parameter is needed to simulate the battery is internal resistance.

Cell and ambient temperatures and the SOC are three main factors which define internal resistance. For simplifying the internal resistance calculations, cell and ambient temperatures have been considered constant during the test. The internal resistance is calculated by [22].

$$R_{int} = \frac{OCV - V_{battery}}{I_{discharging}} \quad (4.4)$$

The internal resistance approaches to an equal value for the value of SOC between 100%-45% after doing different tests on the battery while it's different value for low values of

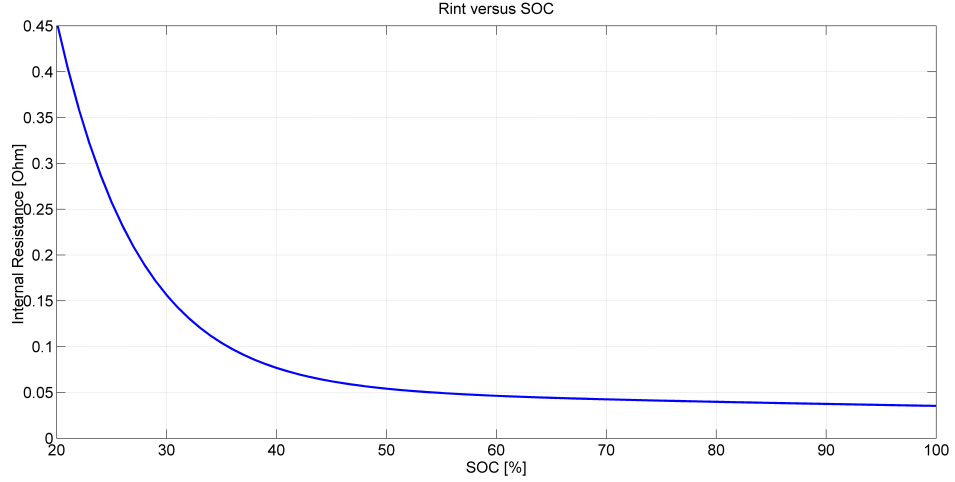


FIGURE 4.4: Zinc Bromide Battery Rint versus SOC.

SOC. This causes some confusion as it indicates seemingly dependent internal resistance on another variables besides SOC, which complicates the modeling of the ZESS if it is true. This issue has been investigated with ZBB Energy experts and an explanation behind this irregularity was found. The main cause of this problem is that insufficient resting time was given during discharging intended for recording measurements of OCV, especially at relatively high current rates [22]. To get the internal resistance relationship with SOC, 80A tests have been done on the battery which gives R_{int} and SOC equation as an exponential interpolate equation.

$$R_{int} = 5.94 * \exp(-0.135 * SOC) + 0.063 * \exp(-5.77e - 3 * SOC) \quad (4.5)$$

Figure 4.4 shows the internal resistance and SOC exponential interpolate curve.

Now, the crucial parameters have been obtained to simulate the battery in Matlab. Below is all simulation figures and simulation results.

In SOC calculation, memory gives us $SOC(0)$, 0.85 is battery efficiency. SOC is calculated according to this equation:

$$SOC = SOC(0) + \frac{0.85 * 100}{3600} \int_0^t \frac{i}{c_n} dt. \quad (4.6)$$

C_n is nominal capacity which is 675Ah.

Now, the internal resistance is considered 45mOhm. Figure 4.11 shows the effect of changing internal resistance in this model.

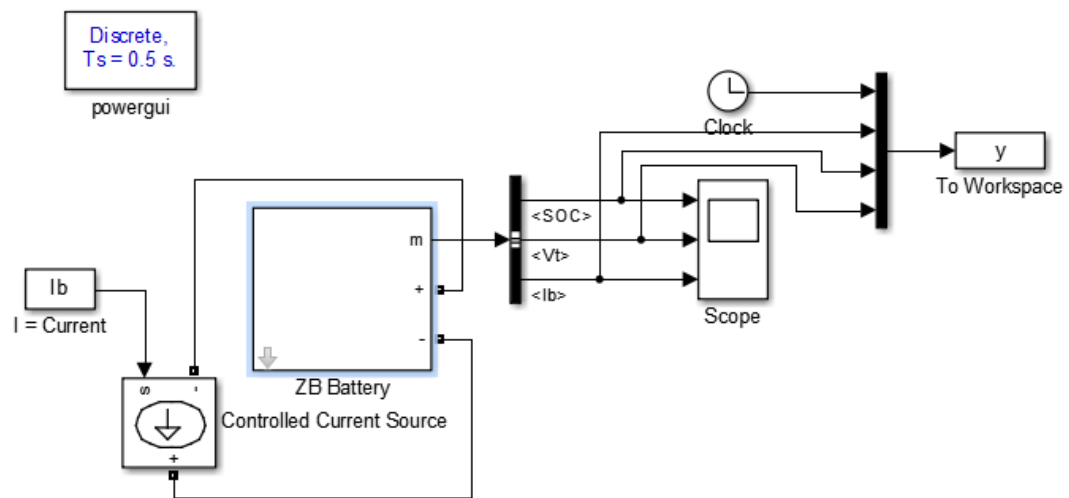


FIGURE 4.5: ZBESS Simulation model.

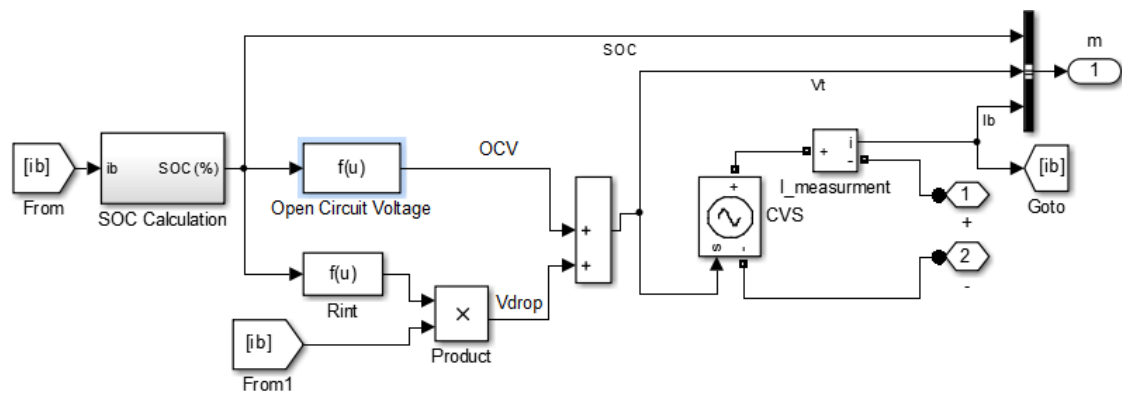


FIGURE 4.6: ZBESS Simulation model .

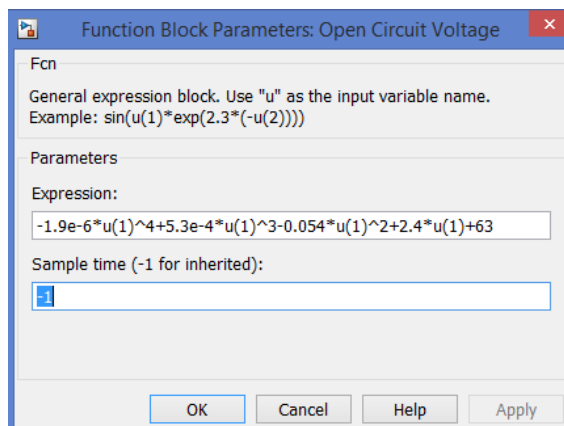


FIGURE 4.7: ZBESS OCV function block.

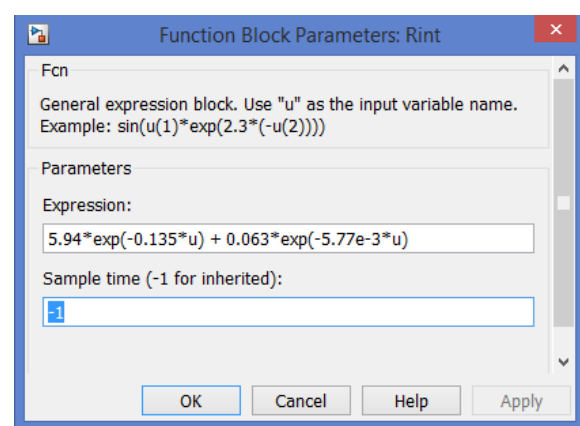


FIGURE 4.8: ZBESS Rint function block.

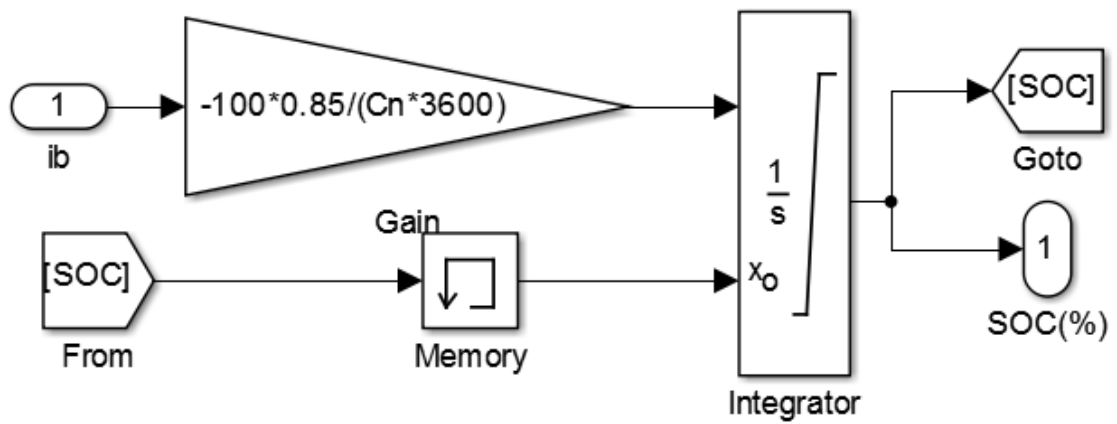


FIGURE 4.9: ZBESS SOC calculation .

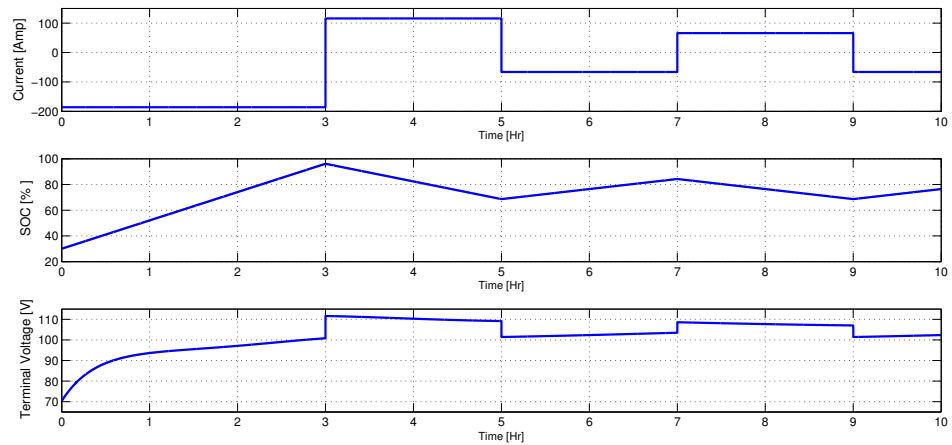


FIGURE 4.10: ZBESS simulation plots .

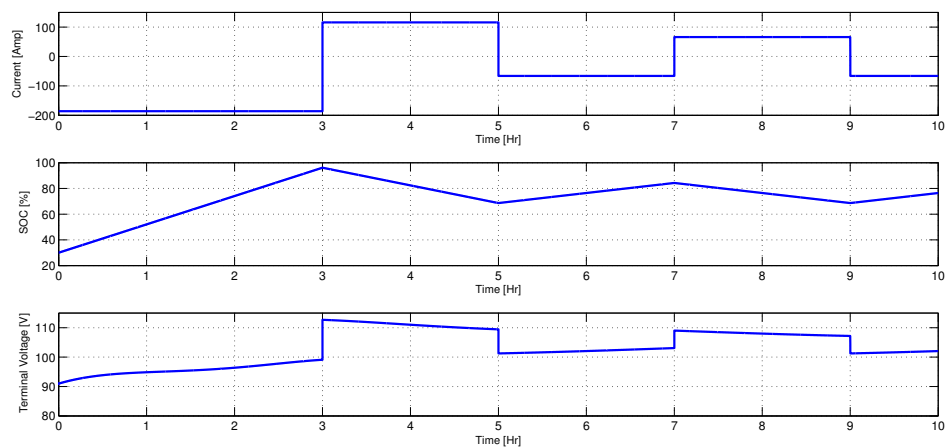


FIGURE 4.11: ZBESS simulation plots when internal resistance is constant.

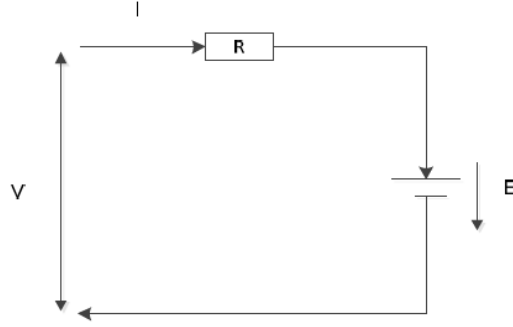


FIGURE 4.12: KiBaM Electrical equivalent model. Based on the concept proposed by James F. Manwell and Jon G. McGowan, Wind power conference, 2005.

4.2 Energyplus Energy Storage System

There are two models for electrical energy storage system in Energyplus: simple model and kinetic battery model. We didn't do any study on Simple model since it doesn't have any special type of energy storage technology. The model we work on it is a kinetic battery model which was originally developed by Manwell and McGowan in 1993.

The Kinetic Battery Model (KiBaM) is based on a chemical kinetics, process to simulate the battery charging and discharging behavior [23]. The Kinetic Battery Model considers two tanks for distributing the battery charge over: an available-charge tank and a bound-charge tank. The available-charge tank can directly provide electrons to the load. It means this part of energy storage capacity is available immediately. The bound-charge tank can only provide electrons to the available-charge tank since it's chemically bound.

Electrical equivalent model for KiBaM (figure 4.12) includes a voltage source in series with an electric resistance. The internal resistance considers constant and the open circuit voltage changes with state of charge and current. The battery voltage can be calculated:

$$V_t = E - RI \quad (4.7)$$

Where R is internal resistance in ohms and I is current in Amps which is positive in discharging and negative in charging.

The battery's open circuit voltage (E) in charge and in discharging is modeled in the same way, but the coefficients are different for charging and discharging. The open circuit voltage changes with the electric current, the state of charge and the operation mode (charging or discharging). For an individual battery module, the open circuit voltage at any time is correlated to the voltage at fully charged/discharged state and

three other regression coefficients. These regression coefficients are usually obtained via curve fitting based on battery test data [23].

$$E_c = E_{0c} + A_c X_c + \frac{C_c X_c}{D_c - X_c} \quad (4.8)$$

$$E_d = E_{0d} + A_d X_d + \frac{C_d X_d}{D_d - X_d} \quad (4.9)$$

Where:

E_{0c} : fully charged battery's Open circuit voltage

E_{0d} : fully discharged battery's Open circuit voltage

A_c, C_c, D_c : charging Constant parameters

A_d, C_d, D_d : discharging Constant parameters

X_c, X_d : Normalized maximum capacity at the given current

A reflects the initial linear variation of internal battery voltage with state of charge. "A" is usually a negative number in discharging mode and positive number in charging mode.

C reflects the battery voltage's increase or decrease when battery is progressively discharged or charged. "C" is always negative in discharging mode, and positive in charging mode.

D reflects the battery voltage's increase or decrease when the battery is progressively discharged or charged." D" is always positive and is normally a number close to the maximum capacity's value.

4.3 ESS Kinetic Battery Model in Energyplus

Now, ZESS should have been simulated according to kinetic battery's open circuit voltage model. As it mentioned before Kinetic battery considers internal resistance constant, so we don't need to find out an equation for R_{int} like what we did for ZESS. We know kinetic battery's Open circuit voltage model (equations 4.8 and 4.9), SO all we need is finding A, C, D, and E_0 for charging and discharging. To find all required coefficients we need to charge and discharge the battery at different current. We have series of tests which has been done on a 50kWh-Zinc Energy Storage System (ZESS) manufactured

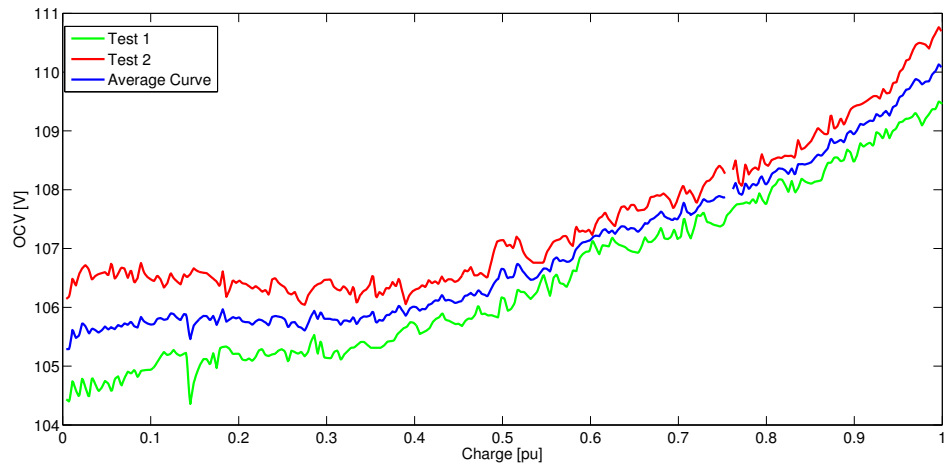


FIGURE 4.13: Kinetic battery OCV versus Capacity in charging mode .

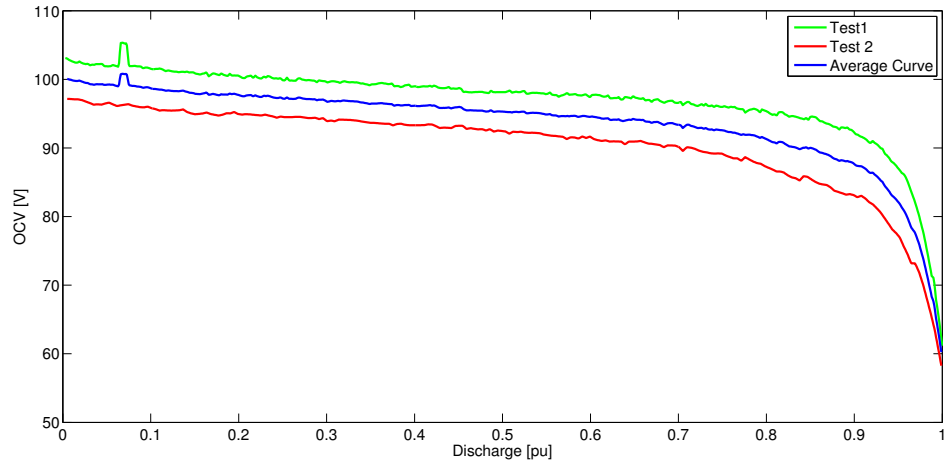


FIGURE 4.14: Kinetic battery OCV versus Capacity in discharging mode .

by ZBB Energy Corporation. The test results help us to find all critical coefficients by using the curve fitting toolbox in Matlab.

Before using the curve fitting toolbox, test result spreadsheets should have been changed to get a proper curve. OCV versus capacity curve in charging and discharging mode is needed. Two test results have been chosen which show the results for charging and discharging ZESS under 80Amps and 150 Amps. The average curves have been gotten out of the two curves for charging and discharging mode. Figures 4.13 and 4.14 show the results.

Now, proper charging and discharging curves are obtained using the curve fitting toolbox in Matlab. Figures show 4.15 and 4.16 the result of kinetic battery fitting charging and discharging curve.

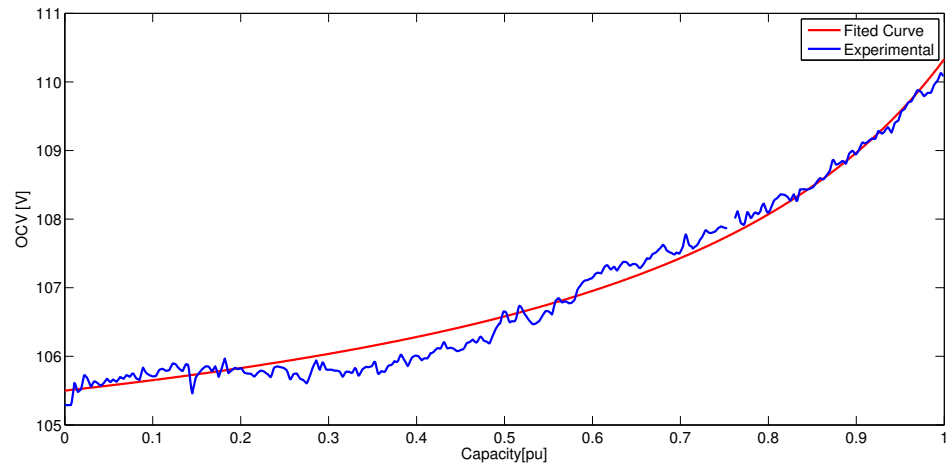


FIGURE 4.15: Kinetic battery fitted curve in charging mode.

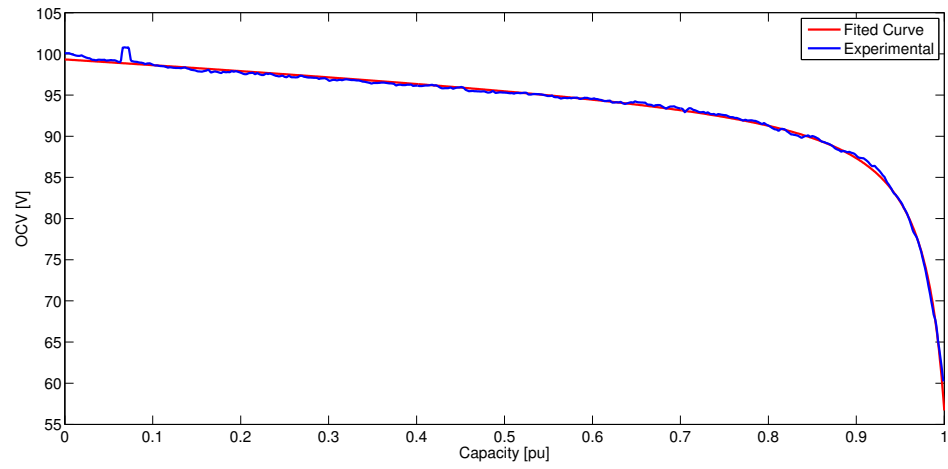


FIGURE 4.16: Kinetic battery fitted curve in discharging mode.

All coefficients have been obtained by the curve fitting tool box as below:

For charging mode:

$$E_0 = 102.5V$$

$$A = 11.128$$

$$C = 5.1792$$

$$D = 0.00381$$

For discharging mode:

$$E_0 = 102.33V$$

$$A = -11.002$$

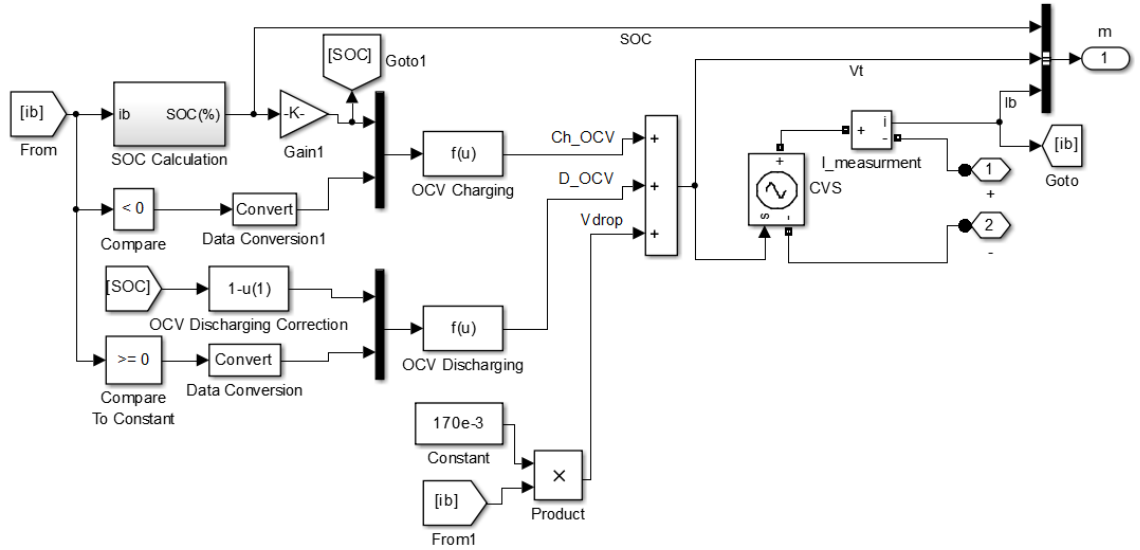


FIGURE 4.17: Kinetic battery simulation .

$$C = -5.9159$$

$$D = 0.0025$$

After getting required coefficients, charging and discharging mode's Energyplus open circuit voltage has been applied in Matlab simulation. Figure 4.17 shows ZESS circuit with Energyplus open circuit voltage model. In this model a condition for the current had been defined. Another signal $u(2)$ is required to apply the current condition. So when $I_b > 0$ (discharging mode) $u(2)$ will be zero and it makes OCV for charging Zero. Also, the OCV for discharging mode should have been corrected. If you see the OCV versus the Capacity curve for discharging mode, you can see when we discharge from for instance 95% to 65%, OCV increases instead of decreasing because of ZESS behavior. SO to correct this issue, the curve had been flipped by block $1-u(1)$.

Figures 4.18 and 4.19 show changes that we made in ZESS model to create a model for Energyplus.

SOC calculation is the same that you can observe it in figure 4.20.

Figure 4.21 shows Kinetic battery simulation results.

4.4 Comparison of ZBB and Kinetic Battery

In this chapter, Zinc bromide battery model and the kinetic battery model will be compared. We consider three different conditions have been studied as below:

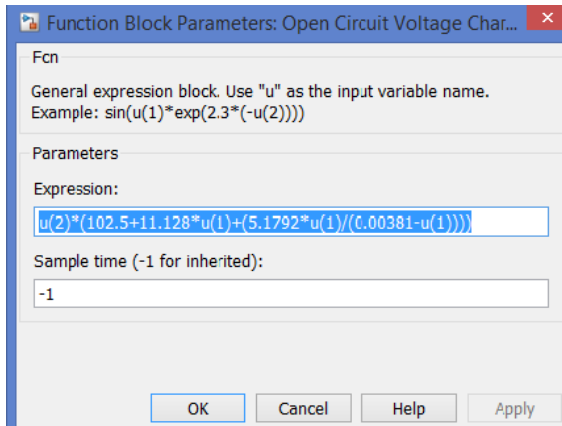


FIGURE 4.18: Kinetic battery OCV function block in charging mode.

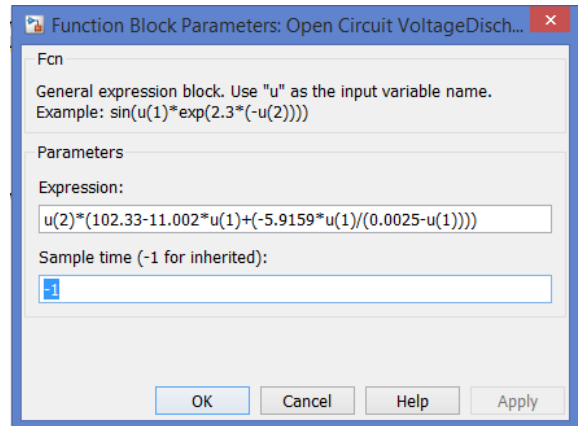


FIGURE 4.19: Kinetic battery OCV function block in discharging mode.

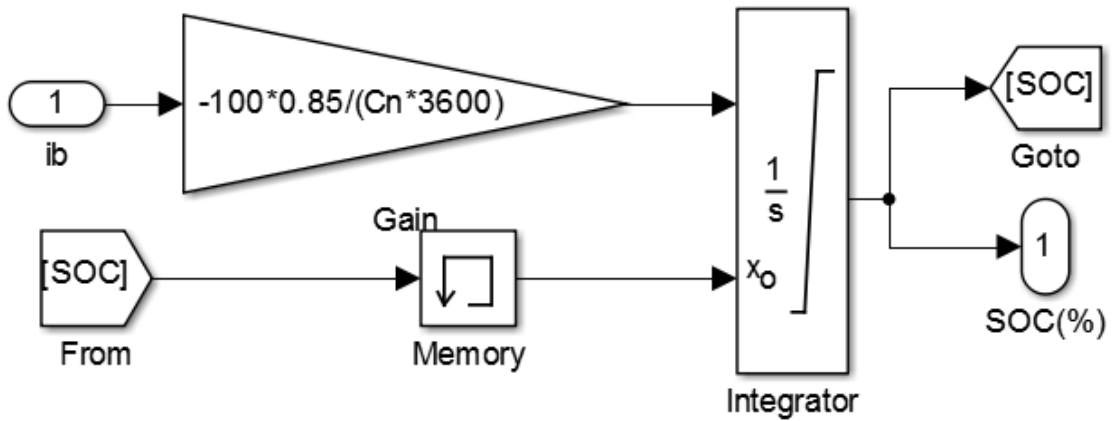


FIGURE 4.20: Kinetic battery SOC calculation.

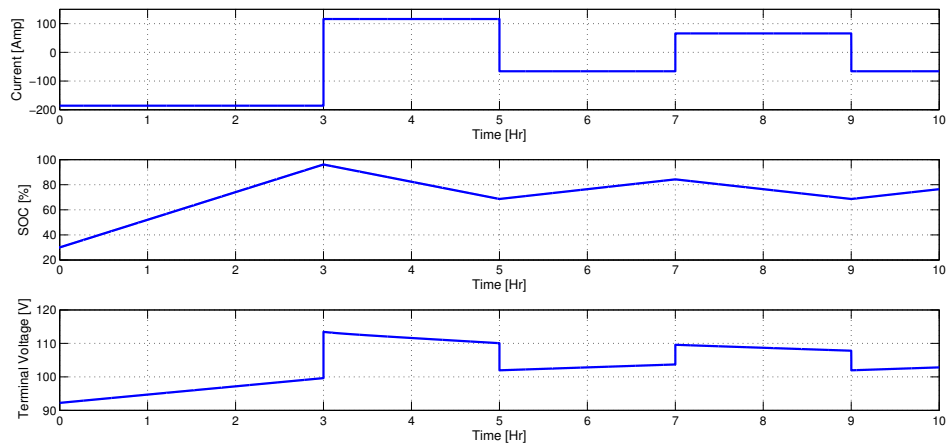


FIGURE 4.21: Kinetic battery simulation plots.

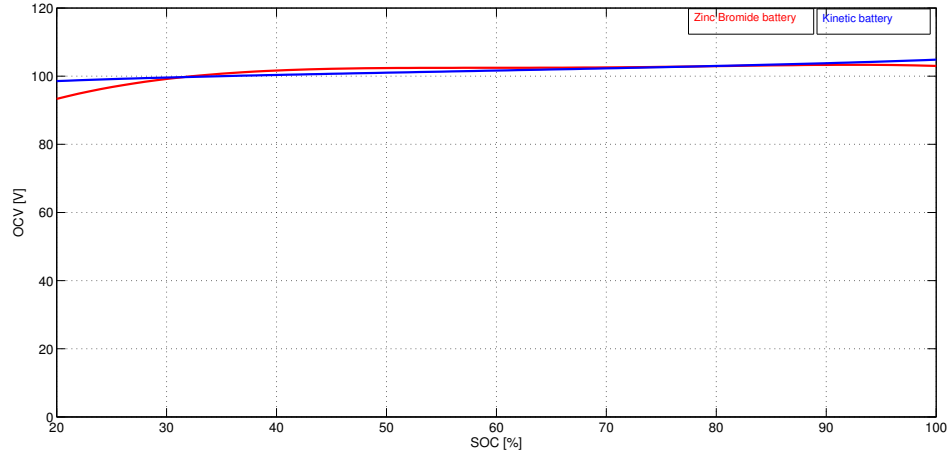


FIGURE 4.22: Comparison Kinetic battery model and ZBESS model's OCV versus SOC.

- OCV equation in Zinc Bromide Energy storage is as below

$$OCV = -1.9 * e - 6 * (SOC)^4 + 5.3e - 4 * (SOC)^3 - 0.054 * (SOC)^2 + 2.4 * (SOC) + 63 \quad (4.10)$$

$$R_{int} = 5.94 * \exp(-0.135 * SOC) + 0.063 * \exp(-5.77e - 3 * SOC) \quad (4.11)$$

- Another assumption in Zinc Bromide Energy Storage is

$$OCV = -1.9 * e - 6 * (SOC)^4 + 5.3e - 4 * (SOC)^3 - 0.054 * (SOC)^2 + 2.4 * (SOC) + 63 \quad (4.12)$$

$$R_{int} = 45e-3 \text{ Ohms}$$

- For kinetic Battery which is modeled in EnergyPlus

$$OCV_{Ch} = 102.5 + 11.128 * SOC + \frac{5.1792 * SOC}{(0.00381 - SOC)} \quad (4.13)$$

$$OCV_{Dis} = 102.33 - 11.002 * SOC + \frac{-5.91592 * SOC}{(0.0025 - SOC)} \quad (4.14)$$

$$R_{int} = 45e-3 \text{ Ohms}$$

At the end, case two and three will be compared. Since Open Circuit Voltage model calculation is different in Kinetic battery with what was modeled for Zinc bromide, we first compare OCV of both models. Figure 4.22 shows the result of the comparison.

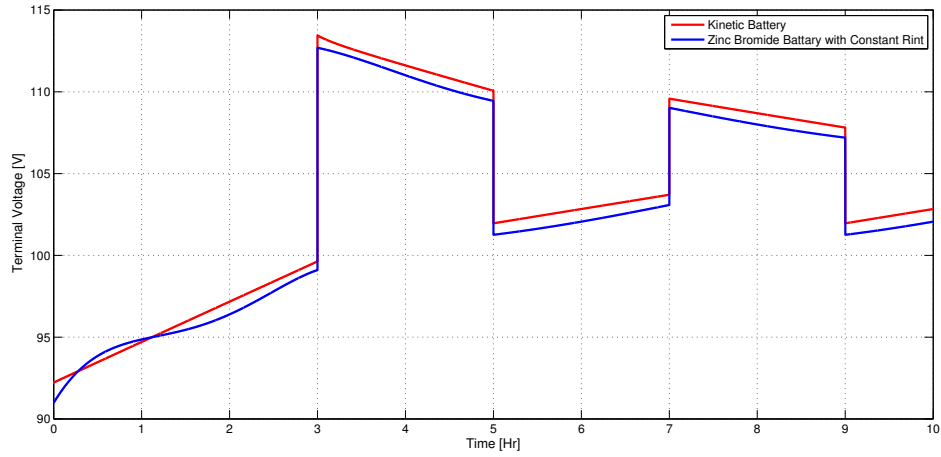


FIGURE 4.23: Comparison Kinetic battery, and Zinc Bromide with constant internal resistant model's terminal voltage.

Another difference that zinc Bromide has with a kinetic battery is internal resistance. Energyplus use kinetic battery so as it's been mentioned the internal resistance is constant for this type of battery while in model ZBESS internal resistance is an exponential equation.

Figure 4.23 shows the terminal voltage comparison for both models. For Zinc Bromide model. As you see in 4.23 we don't have polynomial behavior at the start point of the Kinetic battery model.

Comparing plots show that both plots have the same internal resistance which is 45×10^{-3} Ohm and almost the same OCV as you saw before in Kinetic battery and Zinc Bromide OCV comparison plot.

The reason for the jump between charging and discharging mode is explained by an example. For example, if we have a 100 V battery with 10 Ohms internal resistance. The battery charges to 110 V with 10 Amps current and then it starts discharging. Its polarity suddenly changes and voltage drop to 90 V. There is a 20 V jump between charge and discharge in terminal voltage.

Now, all required EnergyPlus' coefficients have been gotten. So next chapter will explain how these coefficients should have been applied in Energyplus and also it will explain integration of Smartbuilds and Energyplus.

Chapter 5

Study Cases

5.1 Overview of the Software SmartBuilds

SmartBuilds shows a district level multiple buildings, energy and power simulation framework. At the building level, the proposed simulation framework, SmartBuilds, leverages EnergyPlus as the core simulation engine for building energy assessment, thereby benefiting from the capabilities of a widely accepted and used state-of-the-art modeling tool [24]. What we want to have at the district level is a simulation and optimization platform that provides the interaction between buildings and the electric grid and also interaction between buildings. SmartBuilds provides the possibility to simulate multiple buildings and operates schedules for electrical energy storage system in buildings to reduce energy consumption at the district level.

As its mentioned in chapter 1, building sector consumes the largest portion of energy in the world. For example, total buildings energy consumption in the U.S. is 40% of the total energy consumption. Also buildings have an important role in increasing greenhouse gas emission. So increasing energy efficiency and reducing buildings energy consumption benefit us socially, environmentally, and economically, which can be done by load shifting or activating energy storage system in the building district. Increasing energy efficiency in the building district causes improving thermal comfort, decreasing peak demand, and reducing total energy costs.

A simulation tool which model a building with thermal and electrical systems is needed to develop smart building systems. EnergyPlus is the most popular one which is developed by DOE and Lawrence Berkeley National Labs. It models any energy flows in the buildings like heating, cooling, lighting, ventilation, and water use. In this project, a new simulation software framework, SmartBuilds, is developed by Marquette university, which is a versatile modular, component-oriented and scalable framework for model

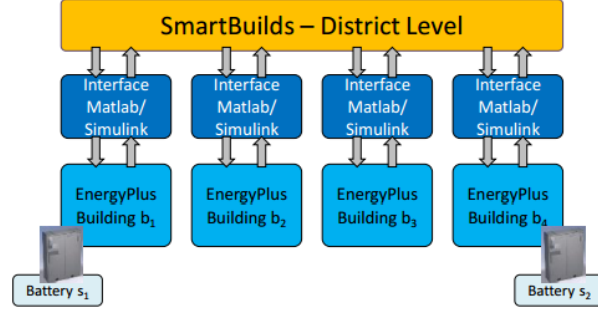


FIGURE 5.1: simplified view of the SmartBuilds simulation framework applied for four buildings. Picture is based on the Concept provided by Shaun Duerr, Electrical Power and Energy Conference, 2015.

and algorithm development, simulation, and testing, to combine building and district models into an integrated approach to capture energy consumption, distribution/supply network, and controls/management in just one model [27]. SmartBuilds overcomes EnergyPlus limitations and bridges like combination with electric power system simulators and focusing on individual buildings without the ability to handle multiple buildings. It develops an algorithm to use energy storage system in the buildings integrated with renewable sources.

European groups develop an Integrated District Energy Assessment by Simulation (IDEAS), a Modelica library for the integrated modeling and simulation of buildings and districts which can describe the built environment, energy consumption and supply, and networks and control in just one model, giving rise to a more effective analysis and better control of the energy system under consideration [24].

SmartBuilds is a new energy and power simulation framework. SmartBuilds simulation framework combines building and district models into an integrated approach to capture energy consumption, distribution/supply network, and controls/management in just one model [24]. Figure 5.1 shows simplified view of the SmartBuilds simulation framework applied for four buildings. In this case, four concurrent EnergyPlus runs are launched to simulate simultaneously the four buildings.

Figure 5.2 shows the proposed simulation frameworks district level block diagram. Each of the nodes in the distribution network represents an agent, which is associated with a building controlled by an individual building management system (BMS). At the top level distribution network or district level SmartBuilds has the ability to invoke electric power system simulators and to solve multi-objective optimization problems that involve multiple buildings [24].

Figure 5.3 shows each agent block diagram. The following three core design principles are developed by BMS (Building Management System) architecture:

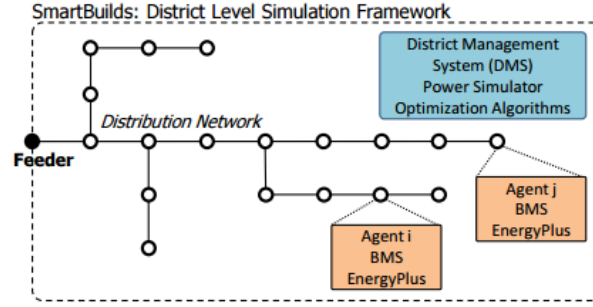


FIGURE 5.2: District level block diagram of the proposed simulation framework. At the building level, the EnergyPlus software is employed as a computational tool. Picture is based on the Concept provided by Shaun Duerr, Electrical Power and Energy Conference, 2015.

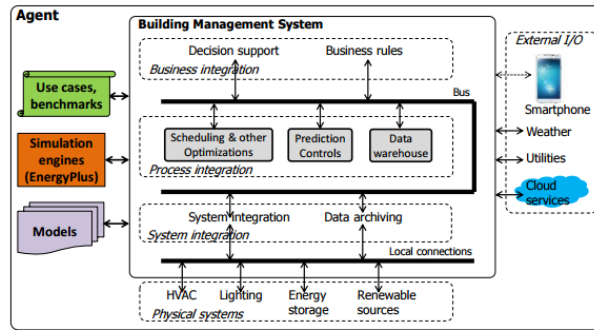


FIGURE 5.3: Individual agent associated with each building. Picture is based on the Concept provided by Shaun Duerr, Electrical Power and Energy Conference, 2015.

- It is a combination of multi-agent and multi-layer architectures which enables hierarchical composition, domain separation, and automatic learning of zone preferences.
- Renewable sources and energy storage systems are incorporated so it provides formulating schedule for using energy storage system.
- It integrates novel methods based on novel energy consumption reporting services so building owners and users can educate toward consumption behavior.

In conclusion, Smart Builds is a district level multiple building energy simulation framework. It overcomes EnergyPlus limitations. Also, it models the interaction between buildings and the electric grid by a versatile simulation and optimization platform. Furthermore, it models the interaction between buildings like energy exchange activities. The proposed simulation framework, SmartBuilds, can simulate multiple buildings rapidly and also can operate Energy storage system schedules to minimize total energy consumption at the buildings level.

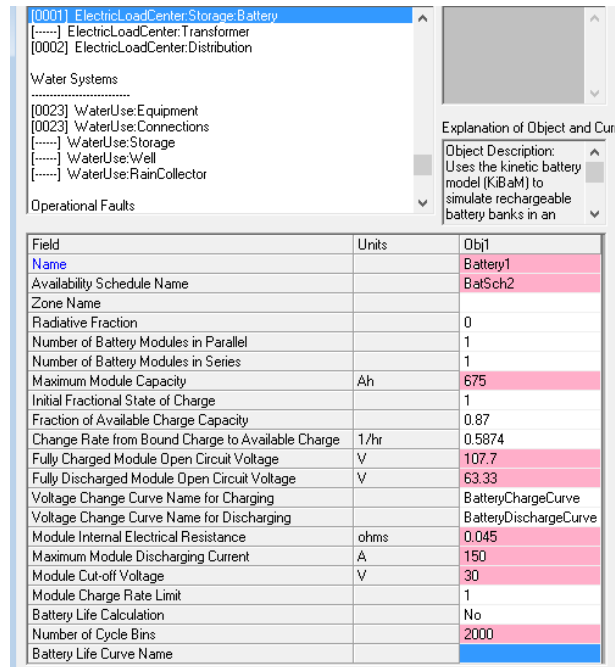


FIGURE 5.4: Electric Load Center Storage/ Battery window in IDF Editor.

5.2 Integration of Battery Model in EnergyPlus

In this chapter, one of the EnergyPlus example file has been used and then a battery and PV have been added to the example. The example building is a four story apartment building which has 31 apartments plus an office. It divided into 27 zones. The building's energy consumption is calculated by EnergyPlus with granularity of minutes, based on the building characteristics and weather conditions. For this example, O'hare, Chicago weather file is used.

As it's explained in chapter 33, we should add some classes in IDF editor to the example file. In chapter 3.3 you can find a list of required classes with short explanation of each class and its required input data. To add a battery following classes should have been added:

- Electric Load Center: Storage: Battery.
- Performance Curves/ curve: RectangularHyperbola2.

Figures 5.4 and 5.5 show entered input data in IDF editor for adding battery in the EnergyPlus example file. In figure 5.5 maximum and minimum Open Circuit Voltage is obtained from OCV versus SOC plot in chapter four.

C1, C2, C3 in Curve Rectangular Hyperbola 2 window are the coefficients we got in chapter four. X is SOC.

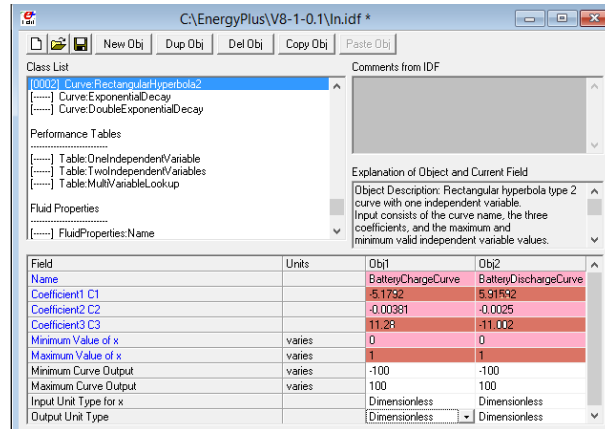


FIGURE 5.5: Curve Rectangular Hyperbola 2 window in IDF Editor.

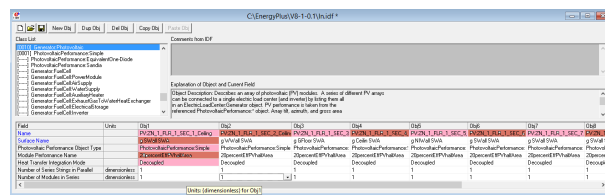


FIGURE 5.6: Generator, Photo voltaic window in IDF Editor.

After adding battery, PV should be added. To add PV in the EnergyPlus example file we need to add following classes in IDF Editor.

- Generator: Photo voltaic.
- Photo voltaic Performance: Simple.
- Electric Load Center: Inverter: Look Up Table.
- Electric Load Center: Distribution.

As you see in figure 5.6 nine PV arrays had been considered for the building. PV model type is simple. Heat transfer integration mode is Decoupled which means the cell temperature of modules in the array is computed based on a energy balance relative to NOCT conditions.

As you see in figure 5.7 conversion efficiency input mode is chosen Fixed so the PV array always has the efficiency value specified in the next field.

$$\text{Efficiency} = (\text{electrical power generated [W]}) / (\text{power of incident solar [W]})$$

In figure 5.8 availability schedule name contains the name of a schedule that describes when the inverter is available. If the inverter is scheduled to not be available, by setting a value of 0, then it cannot produce AC power. Any non-zero schedule value means

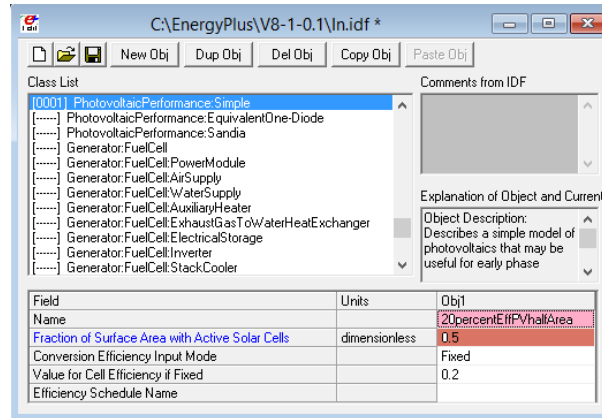


FIGURE 5.7: Photo voltaic Performance, Simple window in IDF Editor.

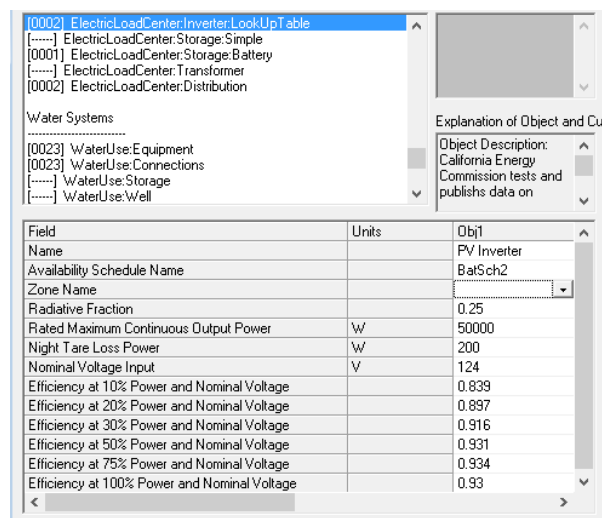


FIGURE 5.8: Electric Load Center, Inverter, Look Up Table window in IDF Editor.

the inverter is available to produce AC power. The rated maximum continuous output power of inverter is 50 KW. The nominal DC input voltage is 124 volts.

In figure 5.9 generator operation scheme type is chosen Track Electrical scheme which means generators try to meet all of the electrical demand for the building.

The purchased power plot is desired to get. So some classes should have been added in EnergyPlus for this purpose. The following classes must be added in IDF editor in the example file in EnergyPlus.

- Energy Management System: Sensor.
- Energy Management System: Actuator.
- Energy Management System: Program.
- Energy Management System: Global Variable.

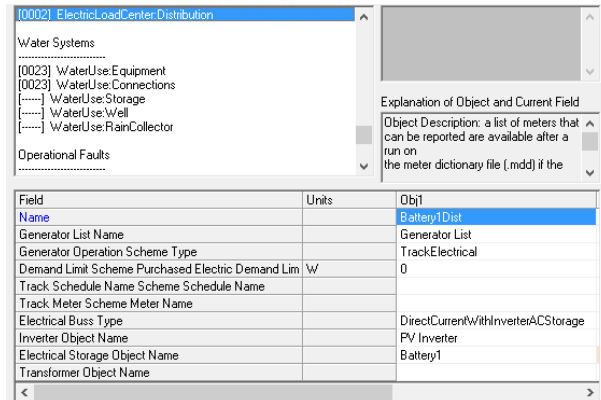


FIGURE 5.9: Electric Load Center, Distribution window in IDF Editor.

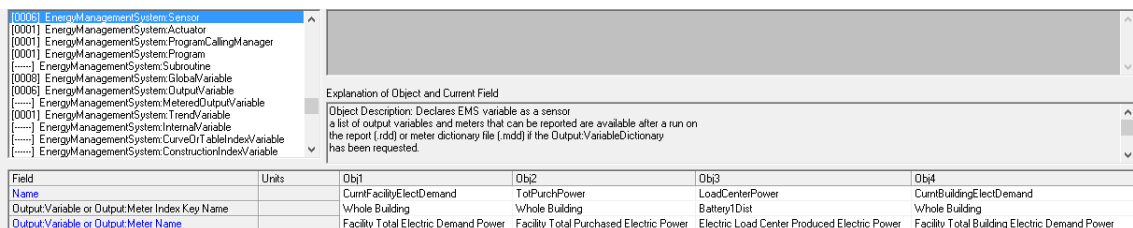


FIGURE 5.10: Energy Management System, Sensor window in IDF Editor.

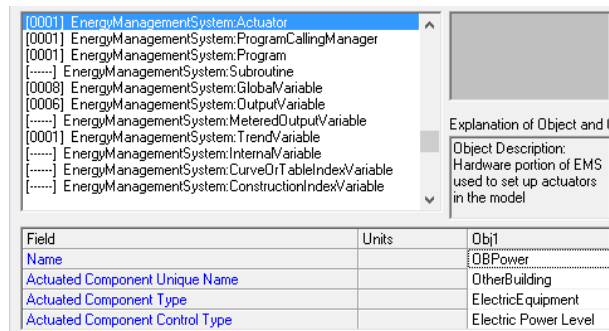


FIGURE 5.11: Energy Management System, Actuator window in IDF Editor.

- Energy Management System: Output Variable.
- Energy Management System: Trend Variable.

In figure 5.10 in filed name we define plot's name and in field output meter name we should find the characteristics we want to track via the .mdd and .rdd files and add it in this field.

In figure 5.11 we should check.edd output file to determine the last three fields.

In figure 5.12 each remaining field contains a single line of code for the EnergyPlus Run time Language, or Erl. Erl is a little programming language with its own syntax.

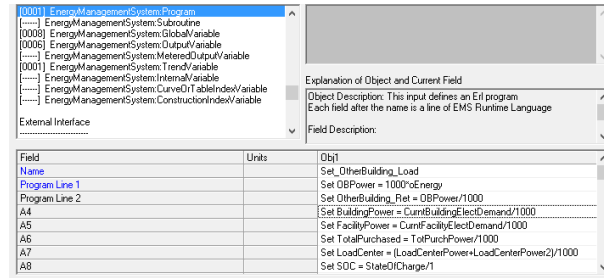


FIGURE 5.12: Energy Management System, Program window in IDF Editor.

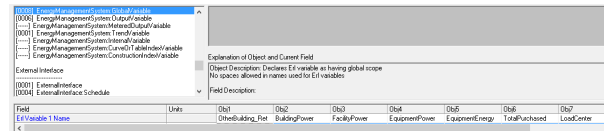


FIGURE 5.13: Energy Management System, Global Variable window in IDF Editor.

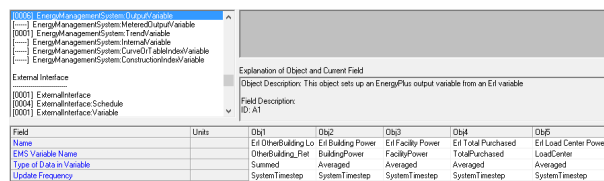


FIGURE 5.14: Energy Management System, Output Variable window in IDF Editor.

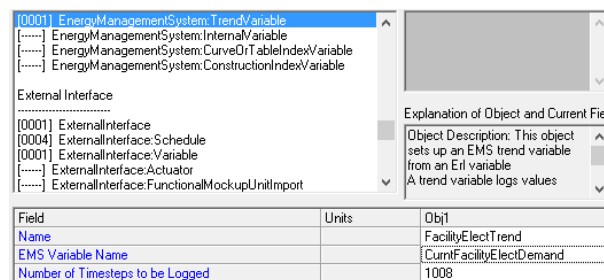


FIGURE 5.15: Energy Management System, Trend Variable window in IDF Editor.

In figure 5.13 the name becomes the global Erl variable name that can be referenced in the EnergyPlus Run time Language. No spaces are allowed in the object name.

In figure 5.14 type of data in variable field is chosen Summed. Summed variables are quantities such as energy that accumulate across time. Also update frequency is chosen System Time step which shows for variables that are related to the HVAC system operation.

In figure 5.15 number of time steps to be Logged is defined 1008 because we considered 42 time steps per hour so for 24 hours it is 1008.

The last three classes are added to create an interface between EnergyPlus and Smart-Builds to communicate and transfer data.

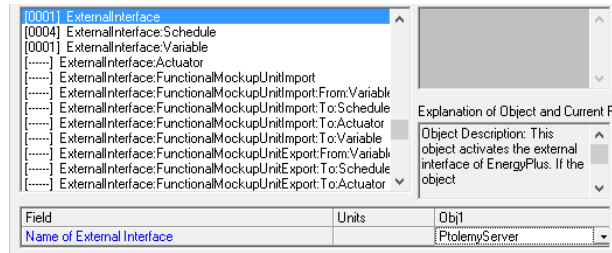


FIGURE 5.16: External Interface window in IDF Editor.

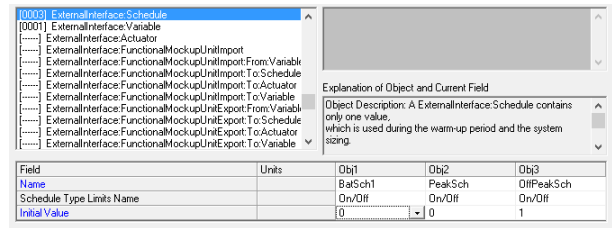


FIGURE 5.17: External Interface, Schedule window in IDF Editor.

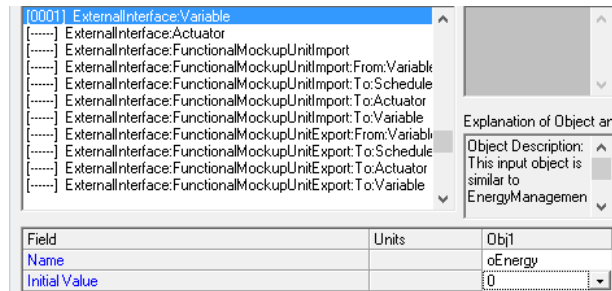


FIGURE 5.18: External Interface, Variable window in IDF Editor.

- External Interface.
- External Interface: Schedule.
- External Interface: Variable.

Figure 5.16 shows an external interface window in EnergyPlus. This object activates EnergyPlus' external interface. If this object is Present, then the external interface objects listed below will receive their value from the BCVTB interface or from FMUs at each zone time step.

In figure 5.17 BatSch1 deals with battery usage, PeakSch and offPeakSch are not useful.

In figure 5.18 oEnergy is used to bring energy from another building into a building.

5.3 Detailed Examples

In the last chapter a battery, photo voltaic, and an inverter had been added to an example in the energyPlus. In this chapter SmartBuilds is used to get some results. The energy consumption is calculated with granularity of minutes by EnergyPlus, based on the building characteristics and weather conditions [24]. SmartBuilds is written with Matlab code by Shaun Duerr in Marquet university. There is a file, building.m, which has important information about the building. In this file EnergyPlus example file and weather file path is defined. Also time step, battery schedule, energy pricing policy is defined. An Energy pricing policy is defined for 24 hours time periods with an hour granularity. Prices can change dynamically in reality, but here prices are assumed known and fixed the day before. To shave the peaks of energy at the building as much as possible and minimize overall energy costs, battery must schedule. Battery schedule, and charges for utility or renewable energy sources should have been determined. Battery schedule is determined in building.m file.

When an example file in EnergyPlus is added or edited, it should be saved. Then a new file should be copied and pasted in SmartBuilds folder. When Smart Builds. m is running, information from building.m will be read and will be provided the results. When SmartBuilds.m is running, Building. m is automatically run and send information to Smart Builds to provide results. SmartBuildsPlot.m contains some code to provide requested plots. The name of plots id defined in Variable.cfg. The plot's name listed in eplusout.rdd.

Smart Builds had been running for an existing example in EnergyPlus. Selected building is a four story apartment which has 31 apartments plus an office. The building's load had been decreased since some limitations in EnergyPlus. The building area is 3135 meter square and it has 27 zones. The example had been running with O'hare weather files for July 1st and July 2nd.

In Smart Builds, the battery is scheduled in building1. m file. The battery schedules to charge between 6a.m to 17 p.m and discharge between 18 a.m to midnight. Unfortunately, there isn't any possibility in EnergyPlus to control the charge and discharge power. Also, PV and its generator are scheduled so PV has the ability to turn on and off.

Variable.cfg is an important file in SmartBuilds. In this file we determine which output must plot. It has a limitation of five Erl and in each run of SmartBuilds the first Erl will plot. SmartBuildsplot.m should run after running SmartBuilds.m to get the defined plot in variable.cfg.

epulosut.err is an error file. If SmartBuilds can't run, this file must be checked to find out the source of errors.

First, SmartBuilds had been running for one day. Four different plots are obtained which you can see in figure 5.19. The plots show the building power consumption for one day when the building doesn't have PV and Battery in red color, building power consumption for one day when the building has PV and Battery in blue color, PV power in green color, and battery power in purple color. To get the load profile with no PV and no battery, in building1.m file PV and the battery had been turned off, then PV and the battery had been turned ON to see the effects of PV and battery on building's load. As you see in 5.19 PV generate power between 8 a.m to 5 p.m which use for the load demand during those hours and the extra power of PV charge the battery. Since extra PV power isn't enough the battery cannot be fully charged. The battery starts discharging during peak hours, 18 p.m. to 23 p.m. It helps us to buy less power from the utility during high demand time. Figure 5.20 shows battery state of charge for one day. As you see battery start charging around 8 am with almost half capacity and it's fully charged around 5p.m. It starts discharging around 7p.m till midnight. As it's mentioned, the battery's amount of charging and discharging couldn't be controlled in EnergyPlus. Also, it has a limitation of adding PV arrays. So these limitations in EnergyPlus don't allow to show the effects of using PV and battery in a residential area in a better way.

In the second case, SmartBuilds is ran for two days. Figure 5.19 shows the building power consumption for one day when the building doesn't have PV and Battery in red color, building power consumption for one day when the building has PV and Battery in blue color, PV power in green color, and battery power in purple color. As you see in the figure 5.19 For a second day battery can't charge and discharge properly, otherwise PV generate more power. If you compare blue and red plots, you can see the advantage of using renewable sources and battery for buildings. It has benefited us economically since purchased power from the utility will be decreased, especially during peak hours, when power has higher price. Also, it improves our environment by reducing pollution. Figure 5.22 shows the battery State Of Charge for two days.

To do a cost analysis, We Energy's company's prices has been chosen. Two price-scheme, on peak and off peak, is used. Residential customers can choose one of four different on peak hours, which are 7 a.m to 7 p.m, 8 a.m to 8 p.m, 9 a.m to 9 p.m, or 10 a.m to 10 p.m. Here, 8 a.m to 8 p.m is considered as on peak hours which is 19.680 cents per KWh. Off peak hour is considered between 9 p.m. to 7 a.m. which is 8.964 cents per KWh and. Figure 5.23 shows We Energies power company's electric rates. Cost analysis has been done in one day and two days run. Two different cases are studied for

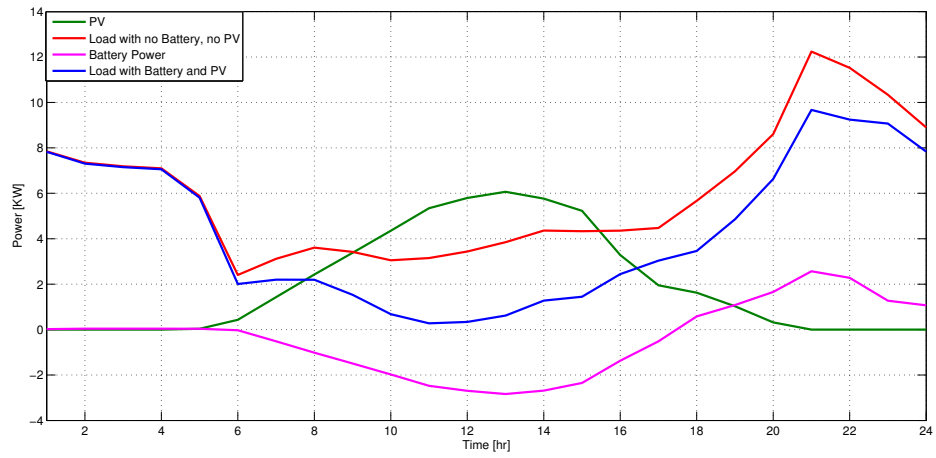


FIGURE 5.19: The building Load profile Comparison for when the building has Battery and PV and when the building has Battery and PV for One Day.

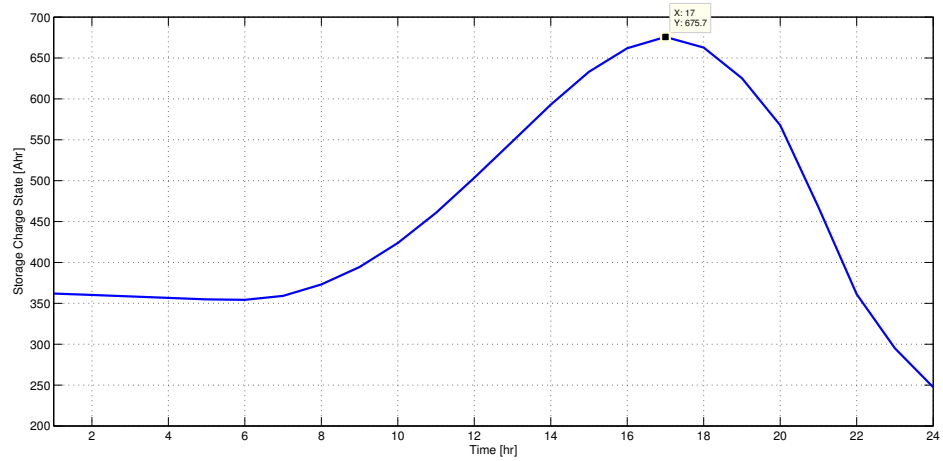


FIGURE 5.20: Battery State of Charge for One Day Run.

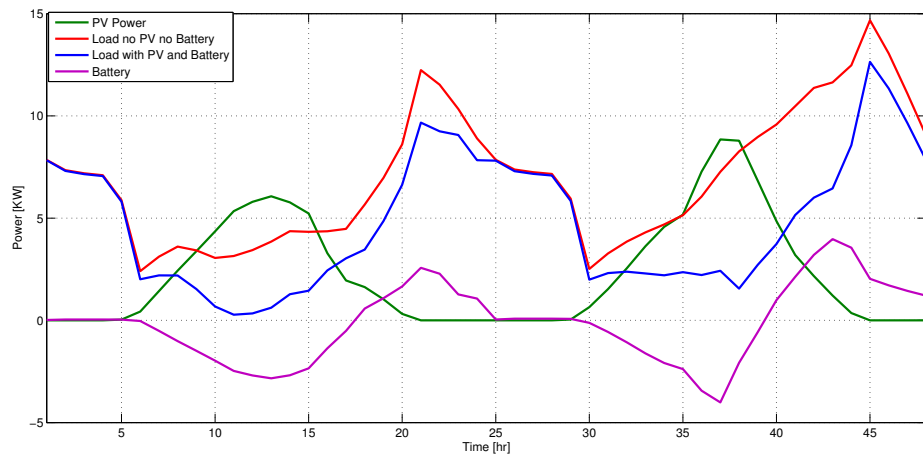


FIGURE 5.21: The building Load profile Comparison for when the building has Battery and PV and when the building has Battery and PV for Two Days.

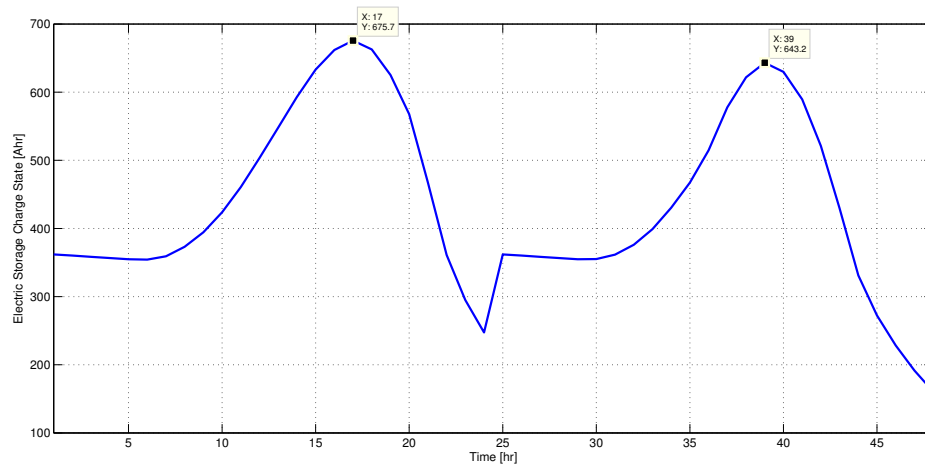


FIGURE 5.22: The building Load profile when we have battery to store produced energy from PV.

Wisconsin Time-of-Use

Residential (Rg2) and Commercial (Cg6)

| Facilities charge (cents/day) | 52.6020 | |
|---|---------|----------|
| Additional meter charge (cents/day) | 5.9510 | |
| | On peak | Off peak |
| Energy charge (cents/kWh) Residential (Rg2) | 19.680 | 8.964 |
| Energy charge (cents/kWh) Commercial (Cg6) | 20.101 | 9.137 |

FIGURE 5.23: We Energies power company's electric rates. Picture is captured from <http://www.we-energies.com/>

one day and two days run. First cost analysis has been done for the building with PV, green building, and then it's been done by taking battery into the green building.

For one day run, when the building has only PV the energy cost is \$ 14.96. When the battery with 85 % efficiency is taken to the building to save surplus renewable energy for the time, which there is no renewable energy production, the energy cost is \$ 12.40. For two day run, the energy cost of green building without battery is \$ 31.80 and when the battery is taken to the green building the energy cost is reduced to \$ 29.11.

As cost analysis results show integrating green building with energy storage minimize total district level energy consumption by increasing local energy generation consumption so it can significantly increase saving in energy consumption and also benefits us economically.

Chapter 6

Conclusion, Contributions, and Future Work

6.1 Conclusion

The focus of the work of this thesis is represented by the analysis of Zinc Bromide Battery and translate Zinc Bromide Battery model to EnergyPlus Kinetic Battery model. In Chapter 1, the research background for the relevant topics was reviewed.

An energy storage system for building sector has been reviewed in Chapter 2. Various types of renewable energy concept are explained in detail. Also, different types of energy storage systems are explained. Then, advantages of integrating building with renewable energy sources are implemented. In addition, some typical energy storage systems are compared to show the suitable energy storage system for buildings.

In chapter 3, Energyplus software is introduced. Also EnergyPlus input data, output data, and file editing have been discussed in this chapter. Furthermore, all classes which should be added or edited in EnergyPlus to get the requested result have been explained with description in each field. Finally an example of building modeling in Energyplus has been running for a building in two scenarios and total energy has been compared.

In chapter 4, first Zinc Bromide Battery battery model is developed by using Matlab Simulink. Then internal resistance is considered a constant value in that model. Also a model for Kinetic battery, which is used in EnergyPlus, is developed. The Kinetic battery model is compared to the Zinc Brmoide battery model with constant internal resistance to show validity of the Kinetic battery model.

In chapter 5, SmartBuilds software, which is developed by Marquette University, is represented. Then added classes in the EnergyPlus IDF editor are explained in details. Finally, an example has been running in two different scenarios, an example building with no PV and no Battery and an example building with PV and Battery. Some plots have been represented to show the benefit of integrating building with renewable energy sources and also using battery in integrating the building with renewable energy sources.

6.2 Contributions

The main contributions resulting from the research covered in the thesis are listed in the following.

1. Kinetic battery model is developed according to Zinc Bromide battery experimental results to get required coefficients to model Kinetic battery in EnergyPlus. The model of Zinc Bromide battery and Kinetic battery are developed in Matlab. Comparing Kinetic battery plots with Zinc Bromide battery plots, which are our source, show accurate results for the Kinetic battery model.
2. SmartBuilds, a district level multiple buildings energy simulation framework which leverages EnergyPlus a state of the art building energy modeling tool as the core simulation engine for building energy assessment, was developed by Marquette university. It provides a versatile platform for the simulation of the interaction between the electric grid and buildings.
3. A battery, PV, and Inverter were added to an example building file in EnergyPlus and then it ran through Smart Builds in two different scenarios. First the building ran without any renewable energy sources and batteries. Then battery and PV were added to the building and also a schedule for the battery ESS has been operated. The result shows that integrating the building with renewable energy sources and battery minimize total district level energy consumption which benefits us economically and environmentally.

6.3 Future Work

Future work is recommended to model a real building in a better software which hasn't EnergyPlus limitations and apply real price for the electricity which changes dynamically. Adding Other renewable energy sources like wind energy is recommended.

From a mathematical point of view, calculating Optimal size of energy storage systems (ESS) in order to maximize energy cost reduction in specified location, occupancy, facility size, and tariffs would be of interest. In addition to calculating the proper size for PV and wind energy in order to rely on clean energy more would be a point of interest.

From an engineering point of view, developing physical models for Wind Turbine which is integrated as modules inside the proposed simulation framework should be considered. Also possibility of operating different battery schedule should be investigated. Furthermore, placement of ESS in grids that can incorporate two types of renewable sources: wind turbines (WT) and photo voltaic (PVs) should be considered for further investigation.

Finally, novel optimization algorithms for new industrial applications of energy storage for demand response, distributed energy generation with renewable sources at building, campus, and district level should be studied and proposed.

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